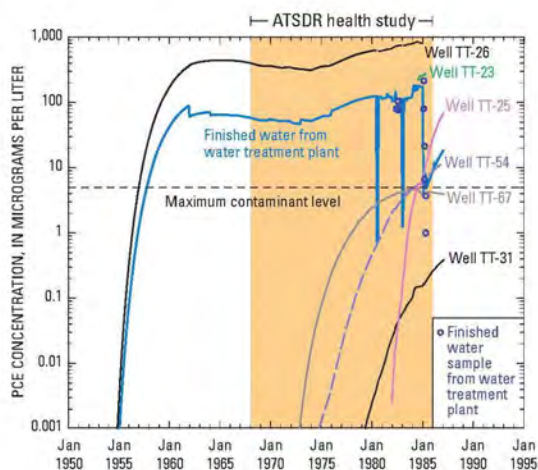


Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)



ATSDR
AGENCY FOR TOXIC SUBSTANCES
AND DISEASE REGISTRY

Atlanta, Georgia—February 2008

Front cover: Historical reconstruction process using data, information sources, and water-modeling techniques to estimate historical exposures

Maps: U.S. Marine Corps Base Camp Lejeune, North Carolina; Tarawa Terrace area showing historical water-supply wells and site of ABC One-Hour Cleaners

Photographs on left: Ground storage tank STT-39 and four high-lift pumps used to deliver finished water from tank STT-39 to Tarawa Terrace water-distribution system

Photograph on right: Equipment used to measure flow and pressure at a hydrant during field test of the present-day (2004) water-distribution system

Graph: Reconstructed historical concentrations of tetrachloroethylene (PCE) at selected water-supply wells and in finished water at Tarawa Terrace water treatment plant

**Analyses of Groundwater Flow, Contaminant Fate and Transport,
and Distribution of Drinking Water at Tarawa Terrace and Vicinity,
U.S. Marine Corps Base Camp Lejeune, North Carolina:
Historical Reconstruction and Present-Day Conditions**

**Chapter F: Simulation of the Fate and Transport
of Tetrachloroethylene (PCE)**

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Foreword

The Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate whether in utero and infant (up to 1 year of age) exposures to volatile organic compounds in contaminated drinking water at U.S. Marine Corps Base Camp Lejeune, North Carolina, were associated with specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at the base. During 2004, the study protocol received approval from the Centers for Disease Control and Prevention Institutional Review Board and the U.S. Office of Management and Budget.

Historical exposure data needed for the epidemiological case-control study are limited. To obtain estimates of historical exposure, ATSDR is using water-modeling techniques and the process of historical reconstruction. These methods are used to quantify concentrations of particular contaminants in finished water and to compute the level and duration of human exposure to contaminated drinking water.

Final interpretive results for Tarawa Terrace and vicinity—based on information gathering, data interpretations, and water-modeling analyses—are presented as a series of ATSDR reports. These reports provide comprehensive descriptions of information, data analyses and interpretations, and modeling results used to reconstruct historical contaminant levels in drinking water at Tarawa Terrace and vicinity. Each topical subject within the water-modeling analysis and historical reconstruction process is assigned a chapter letter. Specific topics for each chapter report are listed below:

- **Chapter A:** Summary of Findings
- **Chapter B:** Geohydrologic Framework of the Castle Hayne Aquifer System
- **Chapter C:** Simulation of Groundwater Flow
- **Chapter D:** Properties and Degradation Pathways of Common Organic Compounds in Groundwater
- **Chapter E:** Occurrence of Contaminants in Groundwater
- **Chapter F:** Simulation of the Fate and Transport of Tetrachloroethylene (PCE) in Groundwater
- **Chapter G:** Simulation of Three-Dimensional Multispecies, Multiphase Mass Transport of Tetrachloroethylene (PCE) and Associated Degradation By-Products
- **Chapter H:** Effect of Groundwater Pumping Schedule Variation on Arrival of Tetrachloroethylene (PCE) at Water-Supply Wells and the Water Treatment Plant
- **Chapter I:** Parameter Sensitivity, Uncertainty, and Variability Associated with Model Simulations of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water
- **Chapter J:** Field Tests, Data Analyses, and Simulation of the Distribution of Drinking Water
- **Chapter K:** Supplemental Information

An electronic version of this report, *Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)*, will be made available on the ATSDR Camp Lejeune Web site at <http://www.atsdr.cdc.gov/sites/lejeune/index.html>. Readers interested solely in a summary of this report or any of the other reports should refer to *Chapter A: Summary of Findings* that also is available at the ATSDR Web site.

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Conversion Factors

Multiply	By	To obtain
Length		
inch	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Area		
square foot (ft ²)	0.09290	square meter (m ²)
square mile (mi ²)	259.0	hectare (ha)
square mile (mi ²)	2.590	square kilometer (km ²)
acre	0.004047	square kilometer (km ²)
acre	0.4047	hectare (ha)
Volume		
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m ³)
million gallons (MG)	3,785	cubic meter (m ³)
Flow rate		
foot per day (ft/d)	0.3048	meter per day (m/d)
foot per year (ft/yr)	0.3048	meter per year (m/yr)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
cubic foot per day (ft ³ /d)	0.02832	cubic meter per day (m ³ /d)
million gallons per day (MGD)	0.04381	cubic meter per second (m ³ /s)
inch per year (in/yr)	25.4	millimeter per year (mm/yr)
Mass		
pound, avoirdupois (lb)	4.535 x 10 ⁻⁴	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
Hydraulic conductivity		
foot per day (ft/d)	0.3048	meter per day (m/d)
Transmissivity		
foot squared per day (ft ² /d)	0.09290	meter squared per day (m ² /d)

Concentration Conversion Factors

Unit	To convert to	Multiply by
microgram per liter (µg/L)	milligram per liter (mg/L)	0.001
microgram per liter (µg/L)	milligram per cubic meter (mg/m ³)	1
microgram per liter (µg/L)	microgram per cubic meter (µg/m ³)	1,000
parts per billion by volume (ppbv)	parts per million by volume (ppmv)	1,000

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

x

Glossary and Abbreviations

1,1,1-TCA	1,1,1-trichloroethane
1,1- and 1,2-DCA	1,1- and 1,2-dichloroethane
AKA	also known as
ATSDR	Agency for Toxic Substances and Disease Registry
BTEX	benzene, toluene, ethylbenzene, and xylene
CLP	Clinical Laboratory Program
DCA	dichloroethane
DCE	1,1-DCE 1,1-dichloroethylene or 1,1-dichloroethene 1,2-DCE 1,2-dichloroethylene or 1,2-dichloroethene 1,2-cDCE <i>cis</i> -1,2-dichloroethylene or <i>cis</i> -1,2-dichloroethene 1,2-tDCE <i>trans</i> -1,2-dichloroethylene or <i>trans</i> -1,2-dichloroethene
GC/MS	gas chromatograph/mass spectrometer
MCL	maximum contaminant level
MODFLOW	original version of the numerical code for a three-dimensional groundwater-flow model, developed by the U.S. Geological Survey
MODFLOW-96	a three-dimensional groundwater-flow model, 1996 version, developed by the U.S. Geological Survey
MT3DMS	a three-dimensional mass transport, multispecies model developed by C. Zheng and P. Wang on behalf of the U.S. Army Engineer Research and Development Center in Vicksburg, Mississippi
NCDNRCD	North Carolina Department of Natural Resources and Community Development
ND	not detected
PCE	tetrachloroethene, tetrachloroethylene, 1,1,2,2-tetrachloroethylene, or perchloroethylene; also known as PERC® or PERK®
PMWINPro™	Processing MODFLOW Pro, version 7.017
RMS	root mean square
TCE	1,1,2-trichloroethene, 1,1,2-trichloroethylene, or trichloroethylene
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
VOC	volatile organic compound
WTP	water treatment plant

Note: The maximum contaminant level (MCL) is a legal threshold limit set by the USEPA on the amount of a hazardous substance that is allowed in drinking water under the Safe Drinking Water Act; usually expressed as a concentration in milligrams or micrograms per liter. Effective dates for MCLs are as follows: trichloroethylene (TCE) and vinyl chloride (VC), January 9, 1989; tetrachloroethylene (PCE) and *trans*-1,2-dichloroethylene (1,2-tDCE), July 6, 1992 (40 CFR, Section 141.60, Effective Dates, July 1, 2002, ed.)

Use of trade names and commercial sources is for identification only and does not imply endorsement by the Agency for Toxic Substances and Disease Registry or the U.S. Department of Health and Human Services.

Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions

Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)

By Robert E. Faye¹

Abstract

Two of three water-distribution systems that have historically supplied drinking water to family housing at U.S. Marine Corps Base Camp Lejeune, North Carolina, were contaminated with volatile organic compounds (VOCs). Tarawa Terrace was contaminated mostly with tetrachloroethylene (PCE), and Hadnot Point was contaminated mostly with trichloroethylene (TCE). Because scientific data relating to the harmful effects of VOCs on a child or fetus are limited, the Agency for Toxic Substances and Disease Registry (ATSDR), an agency of the U.S. Department of Health and Human Services, is conducting an epidemiological study to evaluate potential associations between in utero and infant (up to 1 year of age) exposures to VOCs in contaminated drinking water at Camp Lejeune and specific birth defects and childhood cancers. The study includes births occurring during the period 1968–1985 to women who were pregnant while they resided in family housing at Camp Lejeune. Because limited measurements of contaminant and exposure data are available to support the epidemiological study, ATSDR is using modeling techniques to reconstruct historical conditions of groundwater flow, contaminant fate and transport, and the distribution of drinking water contaminated with VOCs delivered to family housing areas. This report, Chapter F, describes the development and calibration of a digital model applied to the simulation of the fate and transport of tetrachloroethylene (PCE) within the Tarawa Terrace aquifer and Castle Hayne aquifer system at and in the vicinity of the Tarawa Terrace housing area, U.S. Marine Corps Base Camp Lejeune, North Carolina. The analyses and results presented in this chapter refer solely to Tarawa Terrace and vicinity. Future analyses and reports will present information and data about contamination of the Hadnot Point water-distribution system.

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Background

U.S. Marine Corps Base Camp Lejeune is located in the Coastal Plain of North Carolina, in Onslow County, south of the City of Jacksonville and about 70 miles northeast of the City of Wilmington, North Carolina. The major cultural and geographic features of Camp Lejeune are shown in Figure F1 and on ²Plate 1 (Maslia et al. 2007). A major focus of this investigation is the water-supply and distribution network at Tarawa Terrace, a noncommissioned officers' housing area located near the northwest corner of the base. Tarawa Terrace was constructed during 1951 and was subdivided into housing areas I and II. Areas I and II originally contained a total of 1,846 housing units described as single, duplex, and multiplex, and accommodated a resident population of about 6,000 persons (Sheet 3 of 18, U.S. Marine Corps Base Camp Lejeune, Map of Tarawa Terrace II Quarters, June 30, 1961; Sheet 7 of 34, U.S. Marine Corps Base Camp Lejeune, Tarawa Terrace I Quarters, July 31, 1984). The general area of Tarawa Terrace is bordered on the east by Northeast Creek, to the south by New River and Northeast Creek, and generally to the west and north by drainage boundaries of these streams.

Groundwater is the source of contaminants that occurred in water-distribution networks at Tarawa Terrace and was supplied to the networks via water-supply wells open to one or several water-bearing zones of the Tarawa Terrace aquifer and Castle Hayne aquifer system. Faye (2007) provides a complete description of the geohydrologic framework at and in the vicinity of Tarawa Terrace (Table F1), including data and maps that summarize the geometry of individual aquifers and confining units.

²In this report, for any reference to "Plate 1," see the Chapter A report (Maslia et al. 2007). Plate 1 also is available on the ATSDR Camp Lejeune Web site at http://www.atsdr.cdc.gov/sites/lejeune/docs/Camp_Lejeune_master_plate.pdf

Background

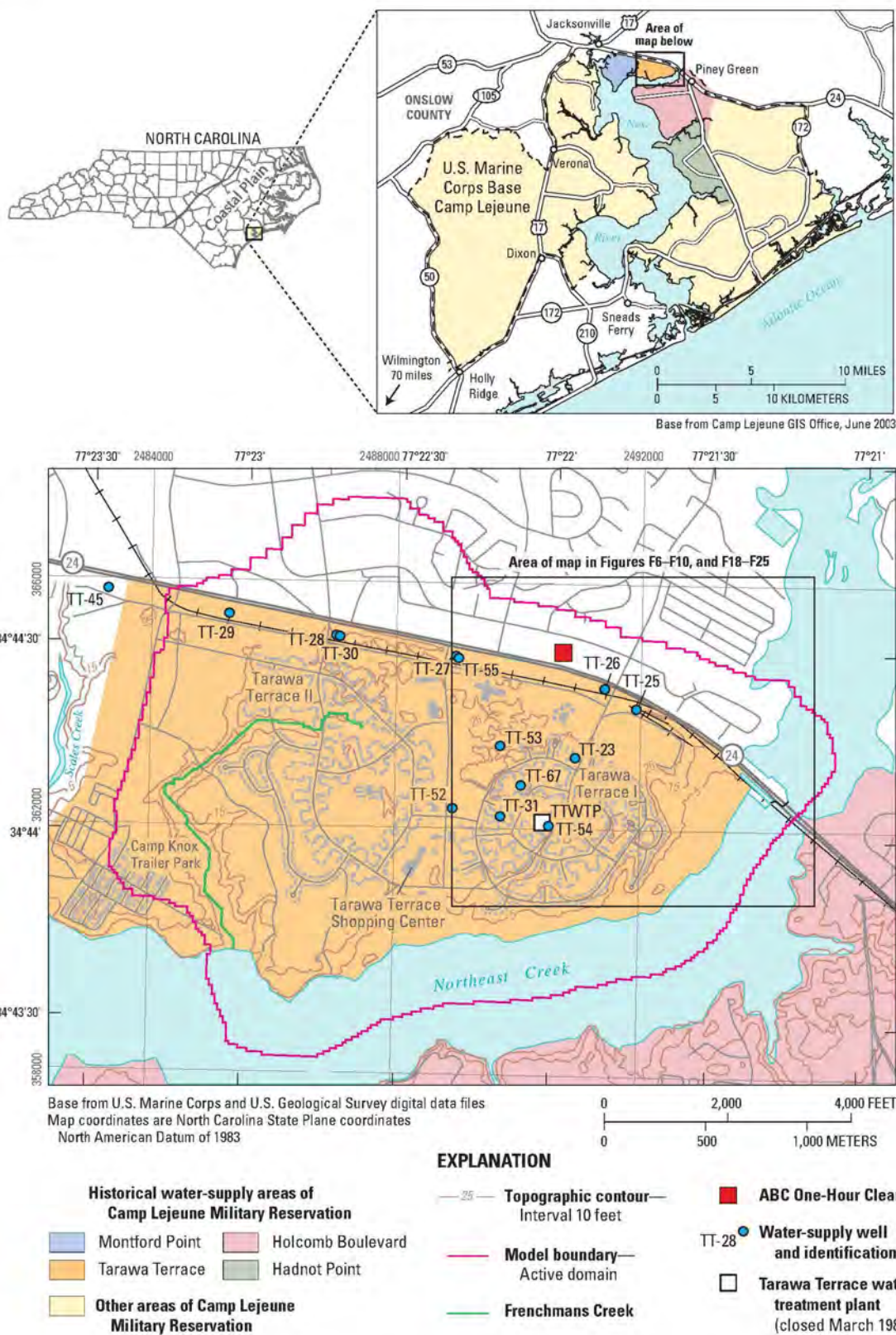


Figure F1. U.S. Marine Corps Base Camp Lejeune, Tarawa Terrace water-supply wells, Tarawa Terrace Shopping Center, and ABC One-Hour Cleaners, Onslow County, North Carolina.

Table F1. Geohydrologic units, unit thickness, and corresponding model layer, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[Units are listed shallowest to deepest and youngest to oldest; N/A, not applicable]

Geohydrologic unit	Thickness range, in feet	Model layer
Tarawa Terrace aquifer	8 to 30	1
Tarawa Terrace confining unit	8 to 20	1
Castle Hayne aquifer system		
Upper Castle Hayne aquifer–River Bend unit	16 to 56	1
Local confining unit	7 to 17	2
Upper Castle Hayne aquifer–Lower unit	8 to 30	3
Middle Castle Hayne confining unit	12 to 28	4
Middle Castle Hayne aquifer	32 to 90	5
Lower Castle Hayne confining unit	18 to 30	6
Lower Castle Hayne aquifer	41 to 64	7
Beaufort confining unit	N/A	

Contamination of groundwater by a halogenated hydrocarbon—tetrachloroethylene (PCE)—was first detected in water supplies at Tarawa Terrace during 1982 (Grainger Laboratories, Camp Lejeune water document CLW 0592, written communication, August 10, 1982). The source of contamination was later determined to be ABC One-Hour Cleaners (Figure F1), located on North Carolina Highway 24 (SR 24) and less than a half-mile west and slightly north of several Tarawa Terrace water-supply wells (Shiver 1985, Figure 4). Production at water-supply wells TT-26 and TT-23 (Figure F1) was terminated during February 1985 because of contamination by PCE and related degradation products—trichloroethylene (TCE), and dichloroethylene (DCE) (Table F2). Trichloroethylene degrades to 1,1-dichloroethylene and 1,2-dichloroethylene and its related isomers *trans*-1,2-dichloroethylene (1,2-tDCE), and *cis*-1,2-dichloroethylene, all of which ultimately degrade to vinyl chloride.

Historical reconstruction characteristically includes the application of simulation tools, such as models, to re-create or represent past conditions. At Camp Lejeune, historical reconstruction methods included linking materials mass balance (mixing) and water-distribution system models to groundwater fate and transport models. Groundwater fate and transport models are based to a large degree on groundwater-flow velocities or specific discharges simulated by a groundwater-flow model. The groundwater-flow model is characterized by the vertical and spatial distribution of aquifers and confining units and their respective hydraulic characteristics, such as hydraulic conductivity and specific storage. Calibration of fate and transport models also requires knowledge of temporal, spatial,

and vertical occurrences of specific contaminant constituents within the water-bearing units open to water-supply and other observation wells. This report describes the simulation of these contaminant occurrences—to the extent possible—given available data and, based on simulated concentrations, summarizes the occurrence of PCE concentrations within the Tarawa Terrace water-distribution system caused by the migration of PCE in groundwater to Tarawa Terrace water-supply wells.

Purpose and Scope of Study

This study seeks to reasonably simulate the migration of PCE in groundwater from the vicinity of ABC One-Hour Cleaners (Figure F1) to the intrusion of PCE into individual Tarawa Terrace water-supply wells. Concentrations of PCE at Tarawa Terrace water-supply wells are simulated at monthly intervals for their entire period of operation, January 1952 through March 1987.³ Simulation of PCE migration in groundwater was accomplished by calibrating integrated groundwater-flow and advection-dispersion models. The computation of PCE concentrations in groundwater delivered to the Tarawa Terrace water treatment plant (WTP), and subsequently distributed through a network of pipelines to base housing, also is summarized herein and was accomplished using a flow-weighted mixing model (Masters 1998).

Geologic Framework

Geologic units of interest to this study are those that occur at or near land surface and extend to a depth generally recognized as the base of the Castle Hayne Formation. The lithostratigraphic top of the Castle Hayne Formation has not been definitively identified. In the northern part of Tarawa Terrace, borehole logs collected in conjunction with the drilling of monitor wells by Roy F. Weston, Inc. (1992, 1994) variously identify the top of the Castle Hayne Formation, “Castle Hayne Limestone,” or the “Castle Hayne aquifer” at or near the top of the first occurrence of limestone or shell limestone, at depths ranging from about 60 to 70 feet (ft) at most sites but ranging in depth to about 90 ft at one location. Borehole and other drillers’ and geophysical logs in the remainder of the study area do not indicate the top of the Castle Hayne Formation. Overlying the limestone or fossiliferous rock in the Roy F. Weston logs is a dark gray silty clay, silt, or sandy silt that ranges in thickness from about 5 to 15 ft. This clay also is identified as a “lean” and sandy clay. For this study, the top of this clay or sandy silt is assigned as the top of the Castle Hayne Formation and is part of a well-recognized, somewhat to highly persistent geohydrologic unit that occurs throughout most of Camp Lejeune east of Northeast Creek (Harned et al. 1989, Sections A–A’, B–B’, and C–C’;

³Simulation stress periods and corresponding month and year are listed in Appendix F1

Geologic Framework

Table F2. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at water-supply wells during ABC One-Hour Cleaners Operable Units 1 and 2, by the North Carolina Department of Natural Resources and Community Development, and by the U.S. Navy, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; #, *cis*-1,2-dichloroethylene; —, constituent not determined; J, estimated value]

Site name	Date	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L	Site name	Date	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
¹ RW1	7/12/1991	² ND	² ND	² ND#	³ TT-26	7/1984	—	⁵ 3.9	—
¹ RW2	7/12/1991	² 760	² ND	² ND#		1/16/1985	⁶ 1,580	⁶ 57	⁶ 92.0
¹ RW3	7/12/1991	² ND	² ND	² ND#		2/12/1985	⁶ 3.8	⁶ ND	⁶ ND
^{3,4} TT-23	7/1984	—	⁵ 37.0	—		2/19/1985	² 55.2	² 3.9	² Trace
	1/16/1985	⁶ 132	⁶ 5.8	⁶ 11.0		2/19/1985	⁶ 64.0	⁶ 4.1	⁶ 9.5
	2/12/1985	⁶ 37.0	⁶ 1.8	⁶ 1.9		4/9/1985	² 630	² 18.0	² 1.4
	2/19/1985	² 26.2	² 53.5	² Trace		6/24/1985	² 1,160	² 24.0	² 5
	2/19/1985	⁶ ND	⁶ ND	⁶ 13.0		9/25/1985	² 1,100	² 27.0	² 1.6
	3/11/1985	²14.9	² ND	² ND		7/11/1991	⁷ 340	⁷ 56J	⁷ ND#
	3/11/1985	⁶16.0	⁶1.3	⁶1.2		7/11/1991	⁷ 360	⁷ 62J	⁷ 15J#
	3/12/1985	²40.6	² ND	² ND	³ TT-30	2/6/1985	⁶ ND	⁶ ND	⁶ ND
	3/12/1985	⁶48.0	⁶2.4	⁶2.8	³ TT-31	2/6/1985	⁶ ND	⁶ ND	⁶ ND
	4/9/1985	² ND	² ND	² ND	³ TT-52	2/6/1985	⁶ ND	⁶ ND	⁶ ND
	9/25/1985	² 4.0	² 0.2	—	³ TT-54	2/6/1985	⁶ ND	⁶ ND	⁶ ND
	7/11/1991	⁷ ND	⁷ ND	⁷ ND#		7/11/1991	⁷ ND	⁷ ND	⁷ ND
³ TT-25	7/1984	—	⁵ Trace	—	³ TT-67	2/6/1985	⁶ ND	⁶ ND	⁶ ND
	2/5/1985	⁶ ND	⁶ ND	⁶ ND					
	4/9/1985	² ND	² ND	² ND					
	9/25/1985	² 0.43	—	—					
	10/29/1985	⁶ ND	⁶ ND	⁶ ND					
	11/4/1985	⁶ ND	⁶ ND	⁶ ND					
	11/12/1985	⁶ ND	⁶ ND	⁶ ND					
	12/3/1985	⁶ ND	⁶ ND	⁶ ND					
	7/11/1991	⁷ 23.0	⁷ 5.8	⁷ 1.4J#					

¹See Figure F6 for location

²Detection limit = 2 µg/L

³See Figure F1 for location

⁴Well TT-23 was operated for 2 hours prior to sampling on 3/11/1985 and 22 hours prior to sampling on 3/12/1985 (**bold**)

⁵Detection limit unknown

⁶Detection limit = 10 µg/L

⁷Detection limit = 5 µg/L

Cardinell et al. 1993, Sections A–A' and B–B'). This unit is designated herein as the Local confining unit. Consequently, contours of equal altitude at the top of the Local confining unit are considered to also approximate the top of the Castle Hayne Formation (Figure F2). As shown, the top of the Castle Hayne Formation occurs near land surface in the northern part of and west of Tarawa Terrace, at altitudes ranging from about –20 to –30 ft, and dips to the east-southeast at a generally uniform rate to the vicinity of Northeast Creek, where

the altitude at the top of the formation is less than –50 ft. Harned et al. (1989) and Cardinell et al. (1993) report that the base of the Castle Hayne Formation occurs at the top of the Beaufort Formation, which is capped by a relatively thick unit of clay, silt, and sandy clay. This clay is named in this report the Beaufort confining unit, following similar usage by Harned et al. (1989) and Cardinell et al. (1993), and is a recognizable unit in logs of deep wells at Camp Lejeune.

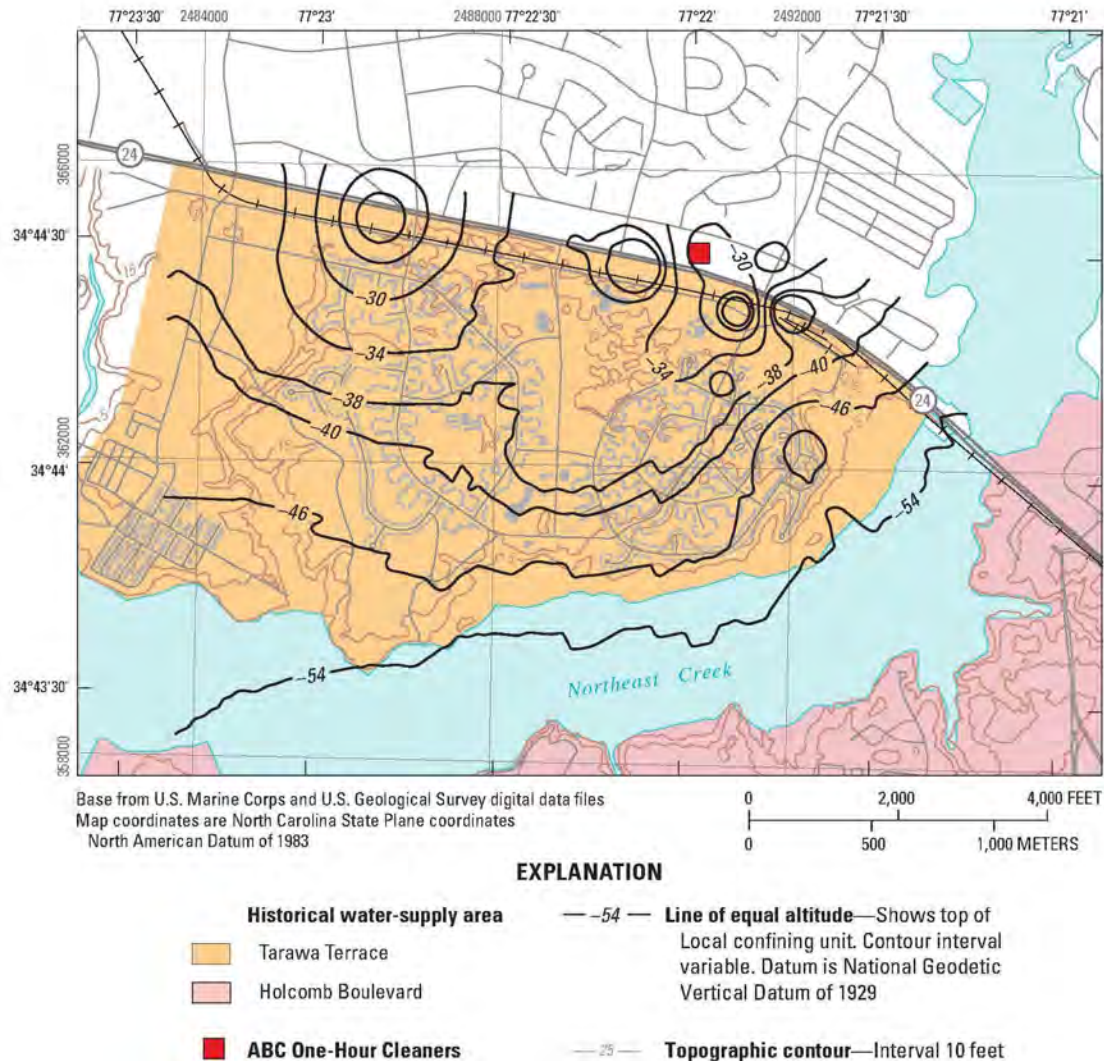


Figure F2. Altitude at the top of the Local confining unit, approximates the lithostratigraphic top of the Castle Hayne Formation, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Geologic Framework

The top of the Beaufort confining unit occurs at about altitude -215 ft in the northern and western parts of the study area and dips gradually to the south and southeast to a minimum altitude of about -250 ft in the vicinity of Northeast Creek (Figure F3). Comparing the maps that show the approximate top and base of the Castle Hayne Formation (Figures F2 and F3), the thickness of the Castle Hayne Formation is shown to range from about 180 ft west of Tarawa Terrace to a maximum thickness of about 200 ft near Northeast Creek (Figure F4). Irregularities of contours shown in Figures F2–F4 are caused by interpolation of the small set of point data used to define the unit altitude or thickness in the study area. The base of the Castle Hayne Formation or the top of the Beaufort confining unit is considered the base of groundwater flow of interest to this study.

In general, the Castle Hayne Formation at Camp Lejeune consists primarily of silty and clayey sand and sandy limestone with interbedded deposits of clay and sandy clay. LeGrand (1959) indicates a “tendency toward layering” with respect to the alternating (with depth) beds of predominantly sandy or clayey sediments. LeGrand (1959) also pointed out that at Tarawa Terrace, Montford Point, and Hadnot Point, the “shellrock is subordinate in quantity to sand” within the Castle Hayne Formation. The sand is fine, often gray in color, and frequently fossiliferous. Much of the limestone is shell limestone, also called “shell hash,” “shellrock,” or coquina in drillers’ logs. Several of the clay deposits, such as the Local confining unit, appear to be continuous and areally extensive (Harned et al. 1989, Sections A–A’, B–B’; Cardinell et al. 1993.

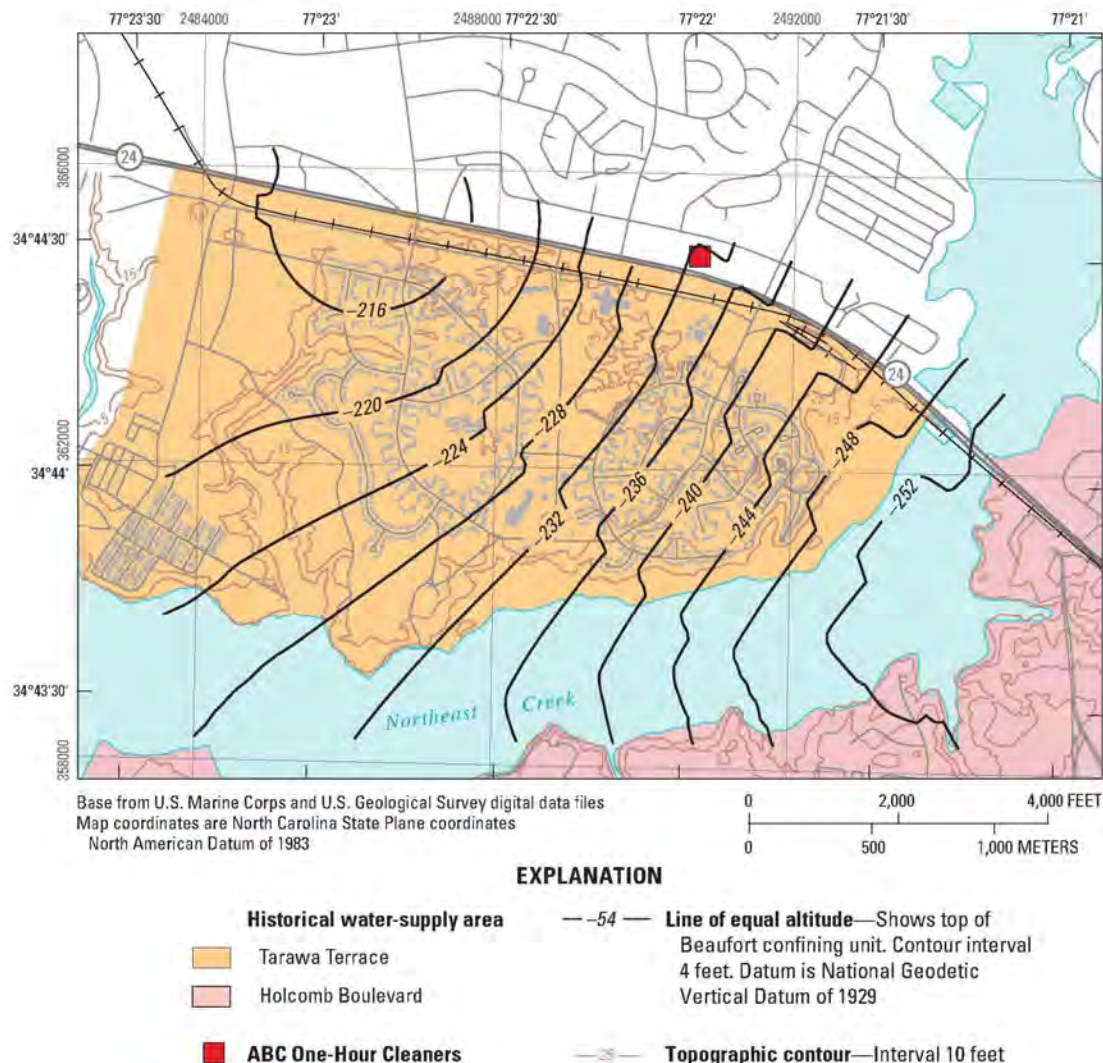


Figure F3. Altitude at the top of the Beaufort confining unit, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Sections A–A', B–B') and range in thickness from about 10 ft to more than 30 ft. Lenticular and discontinuous clay units probably occur frequently. The occurrence of limestone also probably is discontinuous, particularly in the vicinity of Tarawa Terrace. Limestone units of the Castle Hayne Formation at Camp Lejeune are marine and likely were deposited in near-shore environments. Clastic units probably are beach deposits or were formed in deltaic or other near shore transitional environments.

Harned et al. (1989) and Cardinell et al. (1993) assigned an Eocene undifferentiated age to the Castle Hayne Formation, and this age is assigned as well in this report. Similarly, they assigned a Paleocene age to the Beaufort Formation at Camp Lejeune, and this age is adopted as well for this study.

Sediments that occur between land surface and the top of the Castle Hayne Formation are variously referred to as the River Bend Formation of Oligocene age and Belgrade Formation of early Miocene age (Harned et al. 1989; Cardinell et al. 1993). These sediments consist mainly of fine to medium, silty, gray and white sand interbedded with clay and sandy clay. Clays and sands are generally unfossiliferous at Tarawa Terrace but are frequently fossiliferous southeast of Tarawa Terrace in the vicinities of Holcomb Boulevard and Hadnot Point (Plate 1), particularly at depths greater than 30 ft. The base of these units conforms to the top of the Castle Hayne Formation (Figure F2) and dips uniformly to the south and southeast. Unit thickness is zero at land surface and ranges from about 50 to 75 ft within the study area.

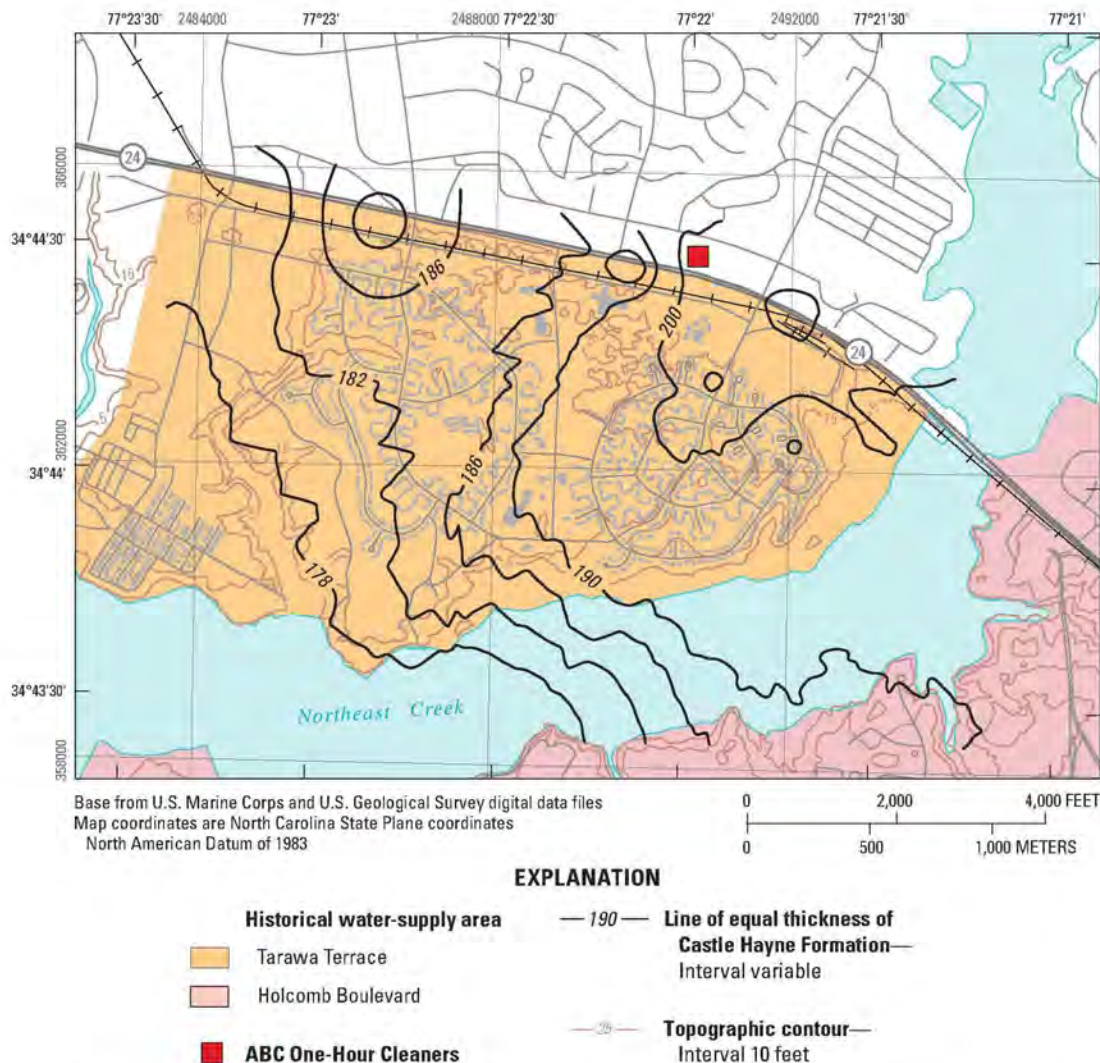


Figure F4. Thickness of the Castle Hayne Formation, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Geohydrologic Framework

A total of nine aquifers and confining units that occur between land surface and the top of the Beaufort Formation in the vicinity of Tarawa Terrace were identified and named after local cultural features where the units were first identified or as subdivisions of the Castle Hayne Formation. From shallowest to deepest these units are the Tarawa Terrace aquifer, Tarawa Terrace confining unit, Upper Castle Hayne aquifer–River Bend unit, Local confining unit, Upper Castle Hayne aquifer–Lower unit, Middle Castle Hayne confining unit, Middle Castle Hayne aquifer, Lower Castle Hayne confining unit, and Lower Castle Hayne aquifer (Table F1). The River Bend unit of the Upper Castle Hayne aquifer is so named to conform to the upper part of the “Castle Hayne aquifer” as described by Cardinell et al. (1993). As defined in this study, the River Bend unit probably includes sediments of the Castle Hayne Formation only at the base, if at all. The Local confining unit separates the River Bend and Lower units of the Upper Castle Hayne aquifer and conforms in areal extent and thickness to the silty or sandy clay described previously at the top of the Castle Hayne Formation (Figure F2). The aquifers and confining units ranging from the top of the Upper Castle Hayne aquifer–River Bend unit to the top of the Beaufort confining unit are inclusive of the Castle Hayne aquifer system, as defined for this study. The water table in the northern part of the study area generally occurs near the base of the Tarawa Terrace confining unit or near the top of the Upper Castle Hayne aquifer–River Bend unit. During periods of significant and prolonged rainfall, the water table possibly resides temporarily near the base of the Tarawa Terrace aquifer; however, sediments equivalent to the Tarawa Terrace aquifer are generally unsaturated. Available water-level data from paired wells individually open to the Upper Castle Hayne aquifer–River Bend and Lower units indicate little or no head difference between the aquifers or a slightly downward gradient from the River Bend unit to the Lower unit (Roy F. Weston, Inc. 1992, 1994). In the southern part of the study area, in the vicinity of the Tarawa Terrace Shopping Center, the Tarawa Terrace confining unit is mainly absent and the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer–River Bend unit are undifferentiated. The water table in this area probably occurs consistently within the middle or base of sediments equivalent to the Tarawa Terrace aquifer.

Altitudes at the top of the Local confining unit and the Beaufort confining unit were shown previously in Figures F2 and F3. Point data used for interpolation control when plotting unit top and thickness generally decrease in number and density with unit depth, increasing the subjectivity of interpolated results. Nevertheless, such maps are considered integral elements of the groundwater-flow model necessary for fate and transport simulation and were used to assign layers and layer geometry during flow-model construction. Contour maps showing altitude at the unit top and unit thickness for all flow-model layers and lists of related point data are included in Faye (2007). Most unit surfaces trend to the south and

southeast and increase in thickness in the same directions, similar to the contours shown in Figures F2 and F3. The tops of most units exhibit a moderate to high degree of irregularity at one or several locations and probably at one or several times following their deposition were erosional surfaces, exposed to the effects of rain, ice, runoff, weathering, dissolution, and similar agents. Accordingly, surface irregularities may represent relict stream channels or hilltops. Where a unit is mainly limestone in composition, surface irregularities possibly represent the remnants of a karst terrain such as sinkholes or related solution or fracture features.

Previous Investigations

Discussions of previous investigations in this report are limited mainly to summaries of remedial investigations of PCE-contaminated groundwater at and in the immediate vicinity of ABC One-Hour Cleaners and within the northern part of the Tarawa Terrace housing area. Summaries of similar investigations for benzene and toluene in the vicinity of the Tarawa Terrace Shopping Center (Figure F1) and elsewhere within the Tarawa Terrace housing areas can be found in Faye (2007), Faye and Green (2007), and Faye and Valenzuela (2007). These reports summarize, as well, the results of investigations of the geohydrologic framework, groundwater contamination, and simulations of groundwater flow within the study area (Figure F1).

During August 1982, routine gas chromatograph/mass-spectrometer (GC/MS) analyses for trihalomethane in water samples collected from the Tarawa Terrace and Hadnot Point WTPs (Plate 1) at U.S. Marine Corps Base Camp Lejeune were interrupted by interference from constituents in the water samples thought to be halogenated hydrocarbons (Grainger Laboratories, Camp Lejeune water document CLW 0592, written communication, August 10, 1982; Elizabeth A. Betz, written communication, August 19, 1982; AH Environmental Consultants, Inc., written communication, June 18, 2004; Camp Lejeune water documents CLW 0592–0595 and 0606–0607). Subsequent analyses confirmed the presence of PCE in samples of finished water supplies from both locations ranging in concentration from 76 to 104 micrograms per liter ($\mu\text{g/L}$) at Tarawa Terrace and from 15 $\mu\text{g/L}$ to not detected (ND) at Hadnot Point. Concentrations of TCE determined in samples from the Hadnot Point WTP ranged from 19 to 1,400 $\mu\text{g/L}$. Samples analyzed were collected during May and July 1982 (Faye and Green 2007, Table E12).

During July 1984, routine sampling and analyses of community water-supply wells at Camp Lejeune, as a part of the Base Naval Assessment and Control of Installation Pollutants Program, indicated the occurrence of TCE in samples obtained from water-supply wells TT-23 (37 $\mu\text{g/L}$), TT-25 (trace), and TT-26 (3.9 $\mu\text{g/L}$) (Maslia et al. 2007). Well TT-26 was open only to the Upper Castle Hayne aquifer, whereas wells TT-23 and TT-25 were open to both the Upper and Middle Castle Hayne aquifers (Faye and Green 2007, Table E2).

Beginning during January and continuing into September 1985, the North Carolina Department of Natural Resources and Community Development (NCDNRCD) periodically sampled water-supply wells TT-23, TT-25, and TT-26 and water treated at the Tarawa Terrace WTP for PCE and its degradation products, TCE, DCE, and vinyl chloride (McMorris 1987). On occasion, duplicate samples were analyzed by NCDNRCD and JTC Environmental Consultants, Inc. (Shiver 1985; R.A. Tiebout, Memorandum for the Commanding General, Chief of Staff, written communication, November 6, 1985; J.R. Bailey to U.S. Environmental Protection Agency, written communication, April 25, 1986; Camp Lejeune water documents CLW 1338–1339 and 1475–1483). Concentrations of PCE in samples from well TT-26 ranged from an estimated 3.8 to 1.580 µg/L in seven samples collected during this period (Table F2). Concentrations of PCE in 10 samples from well TT-23 ranged from “not detected” to 132 µg/L. Concentrations also were detected of TCE, 1,2-tDCE, and vinyl chloride. Tarawa Terrace water-supply wells TT-30, TT-31, TT-52, TT-54, and TT-67 (Figure F1) also were sampled once during this period, and subsequent analyses detected no concentrations of PCE or related degradation products above detection limits at these wells (JTC Environmental Consultants Report 85-047, Report 19, written communication, February 5–6, 1985). However, JTC Environmental Consultants detected benzene at a concentration of 6.3 µg/L in a sample collected at well TT-23 on February 19, 1985 (JTC Environmental Consultants Report 85-072, Report 37, written communication, March 1, 1985). An estimated concentration of PCE of 0.43 µg/L was determined in a sample from well TT-25 during September 1985 (Table F2). Results of sampling and analyses for volatile organic compounds (VOCs) during January and February 1985 caused wells TT-23 and TT-26 to be removed from service during February 1985. Well TT-26 was permanently closed at that time; however, well TT-23 was used to deliver water to the Tarawa Terrace WTP for several days during March and April 1985 (Camp Lejeune water document CLW 1182; Camp Lejeune water document CLW 1193, “Direction to Operators at Tarawa Terrace,” April 30, 1985; Camp Lejeune water document CLW 1194, “Procedures for operating the ‘New Well’ at Tarawa Terrace,” date unknown). At the time of discovery of PCE and related contaminants at Tarawa Terrace water-supply wells, the Tarawa Terrace WTP provided drinking water to about 6,200 people in the service area (McMorris 1987). A summary of analyses of water samples collected at Tarawa Terrace and nearby water-supply wells is listed in Table F2. Location coordinates of Tarawa Terrace and nearby water-supply wells are listed in Table F3.

During April 1985, the NCDNRCD began a field investigation to determine the source or sources of PCE and related constituents occurring in water-supply wells TT-23 and TT-26. Samples were collected at these wells and at well TT-25 for analyses of VOCs. Three monitor wells were installed in the “Water Table aquifer” northwest of well TT-26 and parallel to SR 24 to collect additional samples and water-level data

Table F3. Location coordinates of water-supply wells, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[AKA, also known as]

Site name	Location coordinates ¹	
	North	East
² 2A	364625	2489025
³ RW1	365150	2489880
³ RW2	364930	2490770
³ RW3	364170	2493350
⁴ #6	369730	2481720
⁴ #7	370500	2481530
⁵ TT-23	363208	2491024
⁵ TT-25	364042	2491984
⁵ TT-26, AKA #1	364356	2491461
⁵ TT-27, AKA #2B	364794	2489026
⁵ TT-28, AKA #3	365058	2487071
⁵ TT-29, AKA #4	365352	2485328
⁵ TT-30, AKA #13	365044	2487130
⁵ TT-31, AKA #14	362224	2489843
⁵ TT-45, AKA #5	365688	2483352
⁵ TT-52, AKA #9	362321	2489060
⁵ TT-53, AKA #10	363360	2489800
⁵ TT-54, AKA #11	362090	2490630
⁵ TT-55, AKA #8	364767	2489070
⁵ TT-67, AKA #12	362730	2490160

¹Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

²See Plate 1 in the Chapter A report (Maslia et al. 2007) for location. Plate 1 also is available on the ATSDR Camp Lejeune Web site at http://www.atsdr.cdc.gov/sites/lejeune/docs/Camp_Lejeune_master_plate.pdf

³See Figure F6 for location

⁴Out of map area, location not shown. North Carolina State Plane coordinates: #6 (highly approximate) North 369730, East 2481720; #7 (highly approximate) North 370500, East 2481530; and TT-45 North 365688, East 2483352

⁵See Figure F1 for location

(Shiver 1985; wells X24B4, X24B5, and X24B6 [shown in Figure F6 and on Plate 1 as B4, B5, and B6, respectively]) (Table F5). Results of analyses of samples collected at supply and monitor wells were sufficient to delineate a highly generalized plume of PCE in groundwater of the aquifer. The north-west apex of the plume was located at monitor well X24B6, immediately opposite the entrance of ABC One-Hour Cleaners at 2127 Lejeune Boulevard (SR 24). The PCE concentration determined in the sample from this well was 12,000 µg/L. These and ancillary water-level data indicating the direction of groundwater flow to the southeast toward well TT-26 pinpointed ABC One-Hour Cleaners as the source of PCE in Tarawa Terrace water-supply wells (Shiver 1985, Figure 4).

Previous Investigations

Table F4. Summary of selected analyses for tetrachloroethylene (PCE) in soil samples collected at ABC One-Hour Cleaners by Law Engineering and Testing Company, Inc., and during ABC One-Hour Cleaners Operable Units 1 and 2.

[µg/kg, microgram per kilogram; ND, not detected; detection limits are unknown; data source: Roy F. Weston 1994, Table 2-4, Figures 2-4, 3-1, and 5-2]

Site name	Location coordinates ¹		Date	Sample depth, in feet	PCE concentration, in µg/kg
	North	East			
² Law #3	364918	2490707	9/10/1986	8.00	5,900
² Law #9	364932	2490717	9/10/1986	4.00	106,000
				8.00	450,000
				12.00	22,000
				16.00	12,000
³ Law #10	364927	2490703	9/10/1986	4.00	1,300
				8.00	110
² Law #11	364927	2490731	9/10/1986	4.00	450,000
				8.00	170,000
² Law #12	364918	2490717	9/10/1986	4.00	720,000
				8.00	860,000
				10.00	820,000
² Law #13	364914	2490731	9/10/1986	4.00	630,000
				8.00	260,000
² Law #14	364906	2490731	9/10/1986	4.00	24,000
				8.00	280,000
² Law #15	364901	2490724	9/10/1986	4.00	12,000
				8.00	18,000
² Law #17	364893	2490719	9/10/1986	4.00	5,600
				8.00	5,800
² Law #18	364901	2490707	9/10/1986	4.00	17,000
				8.00	6,000
² SB-1	364874	2490691	6/26/1991	6.00	640
				10.00	37
				14.00	440
³ SB-2	364930	2490697	6/26/1991	2.00	10
				6.00	19
				10.00	27
				14.00	ND
³ SB-3	364981	2490754	6/27/1991	6.00	ND
				10.00	ND
				14.00	ND
³ SB-4	364985	2490736	6/27/1991	12.00	ND
				16.00	ND
³ SB-5	364795	2490714	6/27/1991	6.00	3
				12.00	ND
³ SB-6	364798	2490696	6/27/1991	12.00	ND
				14.00	ND
³ SB-10	364857	2490750	6/30/1991	6.00	2,100
				10.00	210
				14.00	90
³ SB-12	364922	2490767	6/30/1991	4.00	ND
				6.00	ND
				12.00	ND
² SB-13	364841	2490658	9/9/1993	1.00	ND
				4.00	ND
				9.00	ND
				14.00	ND
² SB-14	364930	2490664	9/9/1993	1.00	90
				4.00	570
				9.00	210
				14.00	ND
² SB-15	364938	2490675	9/9/1993	1.00	20
				4.00	ND
				9.00	ND
				14.00	ND
² SB-16	364855	2490726	9/10/1993	1.00	49,000
				4.00	27,000
				9.00	200
				14.00	390

Previous Investigations

Table F4. Summary of selected analyses for tetrachloroethylene (PCE) in soil samples collected at ABC One-Hour Cleaners by Law Engineering and Testing Company, Inc., and during ABC One-Hour Cleaners Operable Units 1 and 2.—Continued
[µg/kg, microgram per kilogram; ND, not detected; detection limits are unknown; data source: Roy F. Weston 1994, Table 2-4, Figures 2-4, 3-1, and 5-2]

Site name	Location coordinates ¹		Date	Sample depth, in feet	PCE concentration, in µg/kg
	North	East			
² SB-17	364834	2490744	9/12/1993	1.00	14
				4.00	1,400
				9.00	650
				14.00	1,400
² SB-18	364859	2490753	9/12/1993	1.00	2,100,000
				4.00	110,000
				9.00	Not sampled
				14.00	Not sampled
² SB-19	364886	2490731	9/15/1993	1.00	300,000
				4.00	4,900
				9.00	16
				14.00	5,100
² SB-20	364918	2490695	9/16/1993	1.00	56
				4.00	Not sampled
				9.00	Not sampled
				14.00	Not sampled
² SB-21	364859	2490703	9/16/1993	1.00	170
				4.00	Not sampled
				9.00	Not sampled
				14.00	Not sampled
² SB-22	364909	2490705	9/17/1993	1.00	580,000
				4.00	210,000
				9.00	26,000
				14.00	2,900
² SB-23	364933	2490738	9/18/1993	1.00	41,600
				4.00	120
				9.00	20
				14.00	44
³ SB-24	364889	2490752	9/21/1993	1.00	ND
				4.00	ND
				9.00	ND
				14.00	ND
³ SPM1	364906	2490730	9/17/1993	1.00	49,000
				4.00	7,500
				9.00	7,100
				14.00	8,900
³ SPM2	364910	2490730	9/15/1993	1.00	4,400
				4.00	14,000
				9.00	15,000
				14.00	6,000
³ SPM5	364902	2490716	9/14/1993	1.00	43,000
				4.00	11,000
				9.00	3,000
				14.00	13,000
³ V1	364899	2490730	9/17/1993	1.00	Not sampled
				4.00	Not sampled
				9.00	33,000
				14.00	180,000
³ V2	364929	2490730	9/17/1993	1.00	180,000
				4.00	5,400
				9.00	2,300
				14.00	800

¹Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

²Roy F. Weston, Inc. 1994, Table 2-4, Figure 2-4

³See Figure F5 for location

Previous Investigations

Table F5. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and total dichloroethylene (DCE) in water samples collected at monitor wells during ABC One-Hour Cleaners Operable Units 1 and 2 and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; J, estimated value; #, *cis*-1,2-dichloroethylene; —, constituent not determined]

Site name ¹	Date	Concentration, in µg/L		
		PCE	TCE	Total DCE
C1	4/24/1992	ND	ND	ND
	9/21/1993	ND	ND	ND
C2	4/23/1992	1J	3J	9J
	10/21/1993	ND	ND	ND
C3	4/29/1992	7J	28	14
	9/23/1993	120	43	21
C4	4/22/1992	ND	ND	ND
	9/22/1993	ND	ND	ND
C5	4/23/1992	ND	17J	ND
	9/22/1993	ND	ND	ND
C9	9/1/1993	0.2J	0.1J	NA
C10	9/1/1993	4.8J	ND	ND
C11	9/1/1993	0.64J	ND	ND
S1	4/24/1992	10	ND	ND
	9/20/1993	27	0.6J	0.2J#
S2	4/23/1992	880	690	1,200
	10/21/1993	490	280	467
S3	4/29/1992	5,400	640	1,200
	9/23/1993	380	24	46J
S4	4/22/1992	ND	ND	ND
	9/20/1993	ND	ND	—
S5	4/23/1992	3	3	ND
	9/22/1993	0.8J	ND	—
S6	4/29/1992	4J	ND	ND
	9/29/1993	0.5J	0.1J	—
S7	4/28/1992	ND	ND	ND
	9/28/1993	0.2J	ND	ND
S8	4/24/1992	ND	ND	ND
	9/28/1993	ND	ND	ND
S9	4/22/1992	ND	ND	ND
	9/23/1993	ND	ND	ND
S10	4/28/1992	ND	ND	ND
	9/22/1993	ND	ND	—
S11	9/29/1993	0.3J	46	ND
² X24B4	9/25/1985	2.2	—	—
² X24B5	9/25/1985	4.9	0.98	—
² X24B6	9/25/1985	12,000	2.7	—

¹See Figure F6 for location

²See Plate 1, Chapter A report, for location (Maslia et al. 2007).

X24B4, X24B5, and X24B6 are shown as B4, B5, and B6, respectively

Detection limit at "C" and "S" sites = 10 µg/L, 5 µg/L, or 1 µg/L.

Detection limit at "X24" sites = 2 µg/L

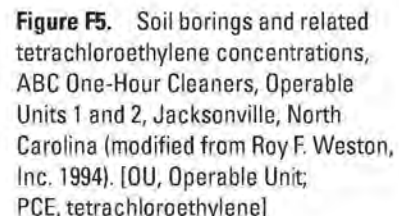
ABC One-Hour Cleaners always used PCE in its dry-cleaning operations, beginning during 1953 when the business opened (Hopf & Higley, P.A., Deposition of Victor John Melts, written communication, April 12, 2001). A primary pathway of contaminants from the dry-cleaning operations at ABC One-Hour Cleaners to the soil and subsequently to groundwater was apparently through a septic tank–soil absorption system to which ABC One-Hour Cleaners discharged waste and wastewater. Shiver (1985) reported that an inspection of the PCE storage area at ABC One-Hour Cleaners indicated that PCE releases could and did enter the septic system through a floor drain, probably as a result of spillage in the storage area (Roy F. Weston, Inc. 1994). In addition, spent PCE was routinely reclaimed using a filtration-distillation process that produced dry "still bottoms" which, until about 1982 (Hopf & Higley, P.A., Deposition of Victor John Melts, written communication, April 12, 2001) or 1984/1985 (McMorris 1987), were disposed of onsite, generally by filling potholes in a nearby alleyway. When ABC One-Hour Cleaners totally discontinued the use of the floor drain and the onsite disposal of still bottoms is not known exactly, but such practices probably terminated completely during 1985.

The disposal of dry-cleaning solvents to the septic system and subsequently to groundwater placed ABC One-Hour Cleaners in violation of various State laws and statutes. During January 1986, the owners were ordered by the State of North Carolina to cease such disposal and propose a plan to restore the quality of affected groundwater to an acceptable level as determined by the State (Roy F. Weston, Inc. 1994). Pursuant to this plan, ABC One-Hour Cleaners hired Law Engineering and Testing Company, Inc., to investigate the septic tank and the surrounding soil for contaminant content. Samples collected and analyzed by Law Engineering and Testing Company, Inc., indicated PCE concentrations of the septic tank sludge were as high as 1,400 milligrams per liter (mg/L) and that soil 4 ft below the tank contained PCE concentrations as high as 400 milligrams per kilogram (mg/kg) (Law Engineering and Testing Company, Inc. 1986a; Roy F. Weston, Inc. 1992). Subsequently, Law Engineering and Testing Company, Inc., conducted additional investigations to determine the vertical and horizontal extent of contamination within the soil profile. These investigations were completed by December 1986 and indicated the depth of PCE contamination in the vicinity of the septic tank to be in excess of 16 ft. PCE concentration at a depth of 8 ft was 860 mg/kg (Law Engineering and Testing Company, Inc. 1986b; Roy F. Weston, Inc. 1992). A summary of PCE concentrations in soil in the vicinity of ABC One-Hour Cleaners is listed in Table F4.

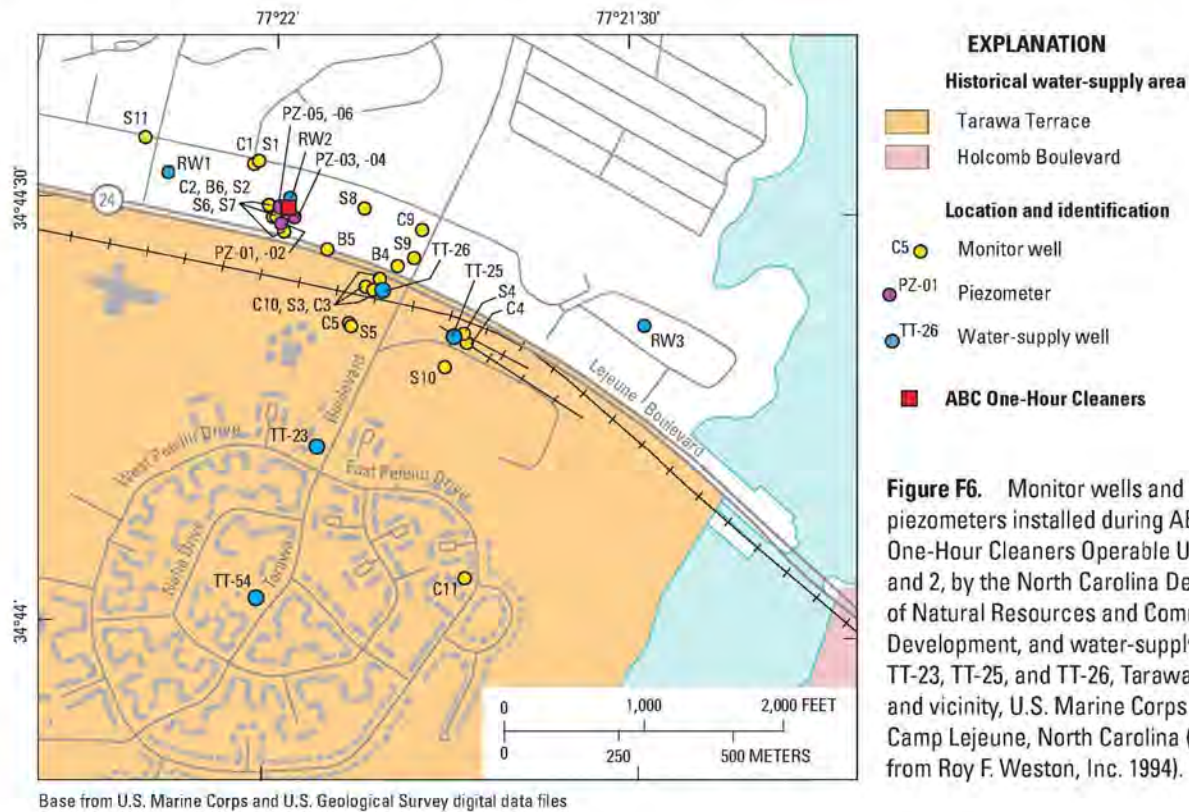
By March or April 1987, all water-supply wells at Tarawa Terrace were removed from service. During March 1989, the ABC One-Hour Cleaners site was placed on the U.S. Environmental Protection Agency's (USEPA) National Priority List (Final List). During June 1990, USEPA hired Roy F. Weston, Inc., to conduct a remedial investigation at the site aimed at determining the areal and vertical extent of contaminant plumes (Operable Unit 1) and characterizing the

Operable Unit 1 of the remedial investigation included the installation of eight soil borings to depths ranging from 16 to 20 ft surrounding and in the immediate vicinity of ABC One-Hour Cleaners (SB-1-SB-6, SB-10, and SB-12; Figure F5, Table F4). These borings occurred entirely within the unsaturated zone. Ten shallow and five deep monitor wells also were installed during Operable Unit 1, not only in the immediate vicinity of ABC One-Hour Cleaners but northwest of the site as well as proximate to water-supply wells TT-25 and TT-26. Several monitor wells also were located between SR 24 (Lejeune Boulevard) and the Tarawa Terrace housing area (Figure F6). The shallow wells, S1-S10, were constructed to depths ranging from 28 to 40 ft and were open at the base of the well to the Upper Castle Hayne aquifer-River Bend

Operable Unit 2 included the construction of an additional shallow well (S11) about 1,000 ft northwest of ABC One-Hour Cleaners. Two additional deep wells, C9 and C10, were constructed east and south of the cleaners. An additional well, C11, was located in the northeast part of the Tarawa Terrace housing area (Figure F6). Depths of the additional deep wells ranged from about 75 to 175 ft. Wells C9 and C11 were open to the Upper Castle Hayne aquifer—Lower unit. Well C10 was open to the Middle Castle Hayne aquifer. Also installed as part of Operable Unit 2 were six piezometers, three shallow (PZ-02, -04, -06) and three deep (PZ-01, -03, -05), in the immediate vicinity of ABC One-Hour



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Cleaners and open to the Upper Castle Hayne aquifer–River Bend and Lower units, respectively. The depths of PZ-02, -04, and -06 ranged from 29.5 to 34.5 ft. Depths of PZ-01, -03, and -05 ranged from 74.5 to 79.5 ft.

Results of analyses of periodic water samples obtained from monitor wells during Operable Units 1 and 2 are summarized in Table F5. Concentrations of PCE ranged from not detected at several wells to 5,400 µg/L at well S3. Samples from monitor wells also were analyzed for various metals and semivolatile compounds. Location coordinates of monitor wells and piezometers constructed during Operable Units 1 and 2 are listed in Table F6.

During Operable Unit 2, similar constituent analysis schedules were used during analyses of effluent from the septic tank at ABC One-Hour Cleaners and of soil samples obtained from the unsaturated zone in the vicinity of the tank. The PCE concentration in the tank effluent was 6,800 µg/L during June 1991. Concentrations of PCE in soil borings at various depths in the immediate vicinity of ABC One-Hour Cleaners ranged from not detected to more than 2,000,000 micrograms per kilogram (µg/kg) (Figure F5, Table F4).

Deep monitor wells C1–C5 were paired with their respective shallow well counterparts S1–S5. Piezometers with odd and even numbers were likewise paired, in an effort to determine vertical hydraulic gradients. Water levels at paired wells and piezometers were measured to hundredths of a foot periodically during 1992 and 1993. Vertical head gradients were

downward at all paired wells at all times with the exception of slightly upward gradients at piezometer sites PZ-01/-02 and PZ-03/-04 during November 1993. A maximum head difference of 2.23 ft occurred at paired wells S1/C1 during April 1992. Head differences between the Upper Castle Hayne aquifer–River Bend unit and the Middle Castle Hayne aquifer were always less than 2 ft. These and similar water-level measurements at all monitor wells were used to map local potentiometric surfaces in the vicinity and downgradient of ABC One-Hour Cleaners. Potentiometric surface maps of the Upper Castle Hayne aquifer–River Bend and Lower units based on these data are shown in Figures F7 and F8. Potentiometric levels in the Tarawa Terrace and Upper Castle Hayne aquifers are similar and range from about 23 to 10 ft, National Geodetic Vertical Datum 1929 (NGVD 29). Potentiometric levels trend from northwest to southeast, from greater to lesser, and generally correspond to groundwater-flow directions. The potentiometric gradient of the Upper Castle Hayne aquifer–River Bend unit ranged from about 0.006 to 0.007 foot per foot (ft/ft) (Roy F. Weston, Inc. 1992). Corresponding gradients for the Upper Castle Hayne aquifer–Lower unit were from 0.005 to 0.006 ft/ft. Aquifer tests were conducted in conjunction with several monitoring wells. Test results indicated that values of horizontal hydraulic conductivity ranged from about 10 to 30 feet per day (ft/d) for the “surficial aquifer” (Upper Castle Hayne aquifer–River Bend unit). Corresponding storativity ranged from magnitude 10^{-4} to 10^{-3} .

Table F6. Location coordinates of monitor wells installed during ABC One-Hour Cleaners Operable Units 1 and 2 and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Site name ¹	Location coordinates ²	
	North	East
C1	365232	2490503
C2	364902	2490793
C3	364437	2491433
C4	364045	2492080
C5	364107	2491233
C9	364800	2491730
C10	364360	2491380
C11	362300	2492130
S1	365251	2490534
S2	364883	2490787
S3	364357	2491413
S4	364065	2492060
S5	364081	2491244
S6	364938	2490617
S7	364753	2490732
S8	364938	2491312
S9	364593	2491682
S10	363818	2491922
S11	365390	2489710
³ X24B4	364530	2491570
³ X24B5	364640	2491050
³ X24B6	364810	2490710

¹See Figure F6 for location

²Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

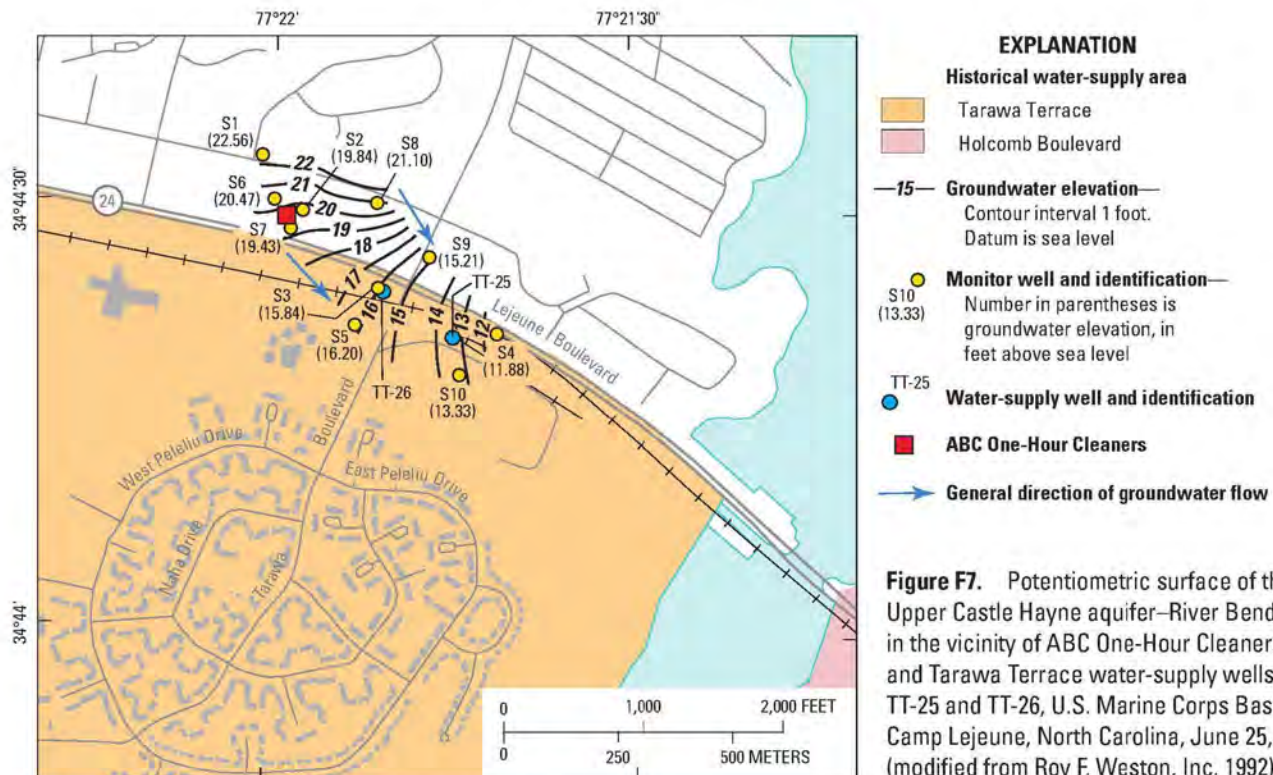
³See Plate I, Chapter A report, for location (Maslia et al. 2007). X24B4, X24B5, and X24B6 are shown as B4, B5, and B6, respectively

In order to characterize the depth, areal extent, and water quality of the contaminant plumes emanating from the vicinity of ABC One-Hour Cleaners, hydrocone penetrations using direct-push technology were accomplished at 47 sites near, east, and south of the cleaners (Figure F9). Two levels of samples were collected at each site, generally at about 20 and 40 ft. The constituent analysis schedule used for hydrocone sample analyses included PCE, TCE, 1,2-*t*DCE, and vinyl chloride, as well as 1,1,1-trichloroethane (1,1,1-TCA), 1,1- and 1,2-dichloroethane (1,1-DCA, 1,2-DCA), and carbon

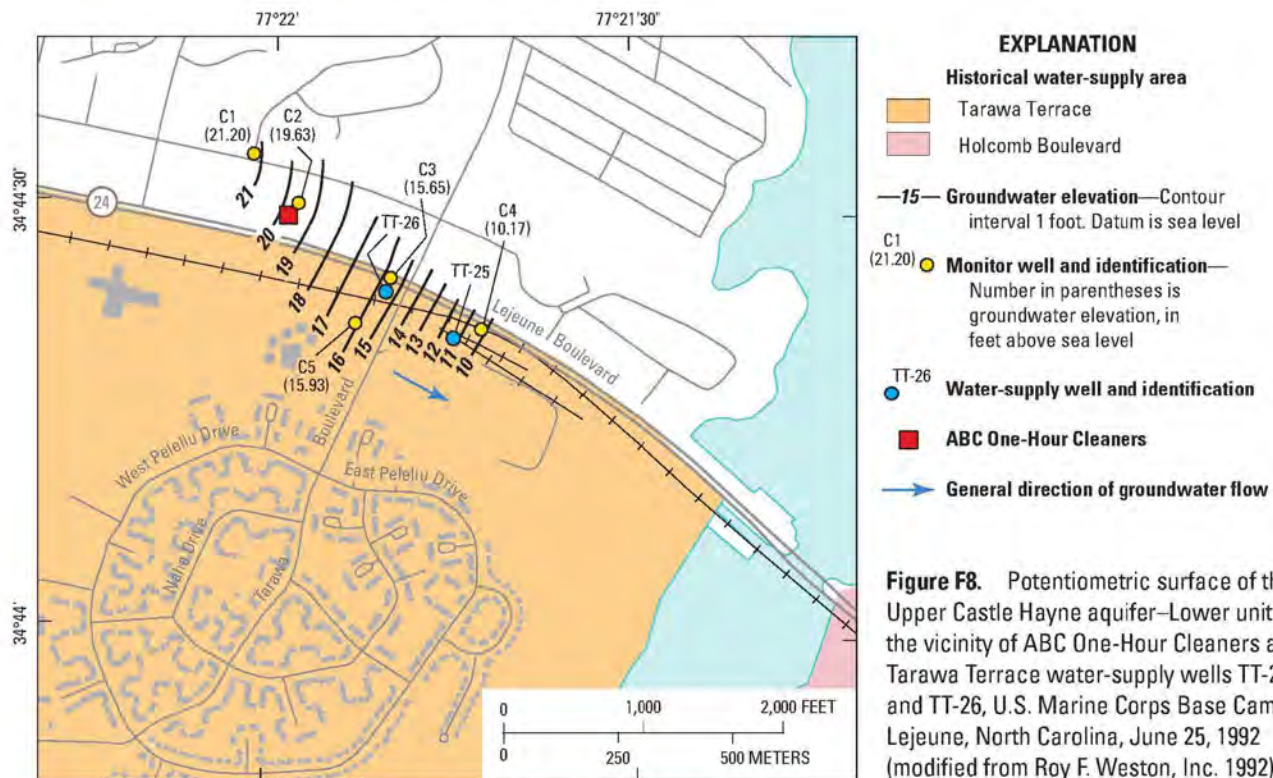
tetrachloride. Samples were analyzed in the field using a mobile laboratory. Several duplicate samples were submitted to "CLP" laboratories for quality assurance of results. Although not defined in the respective Operable Unit reports, CLP probably refers to "Clinical Laboratory Program," a process of inspection of State and Federal public health laboratories for purposes of certification. The CLP laboratories also determined concentrations of benzene, toluene, ethylbenzene, and total xylenes (BTEX compounds), in addition to the constituents discussed previously. Benzene and related toluene, ethylbenzene, and total xylenes were detected infrequently in the hydrocone samples. Benzene concentrations ranged from not detected to 12 µg/L. Results of mobile and CLP laboratory analyses were not highly consistent (Roy F. Weston, Inc 1992, Table 5-12); however, most constituents were noted in one or more samples. PCE was detected most frequently and was found in 75 samples at concentrations ranging from 1 to nearly 30,000 µg/L. The maximum depth of PCE occurrence determined by hydrocone penetration was 64 ft (sample HC-6-64), which is near the base of or slightly below the Upper Castle Hayne aquifer—River Bend unit at the sample location. Results of analyses of water samples collected during hydrocone penetration investigations are summarized in Table F7. Location coordinates of hydrocone penetration sites are listed in Table F8. Construction data for Tarawa Terrace water-supply wells are listed in Table F9. Similar data for monitor wells and piezometers constructed during ABC One-Hour Cleaners Operable Units 1 and 2 are listed in Table F10. A contour map based on PCE concentrations observed at Tarawa Terrace water-supply wells, monitor wells, and hydrocone penetration sites during 1991 and 1993 is shown in Figure F10. Concentrations represent data from the Upper Castle Hayne aquifer—River Bend and Lower units. The center of PCE mass at the time occurred southeast of ABC One-Hour Cleaners near the intersection of SR 24 and Tarawa Boulevard. This center of mass originally occurred in the immediate vicinity of ABC One-Hour Cleaners, and its location during 1991 and 1993 indicates that migration of the PCE mass apparently occurred advectively, mainly along potentiometric gradients (Figures F7 and F8).

During 1990, ATSDR completed an assessment of public health effects related to groundwater contamination at ABC One-Hour Cleaners and expressed a public health concern that off-site (namely Tarawa Terrace) exposure of contaminants to humans had occurred through the groundwater pathway. During 1997, ATSDR conducted a comprehensive Public Health Assessment of U.S. Marine Corps Base Camp Lejeune, which included an assessment of human exposure to contaminated groundwater at Tarawa Terrace. Maximum contaminant concentrations for PCE (215 µg/L), TCE (8 µg/L), and DCE (12 µg/L) determined from samples obtained within the Tarawa Terrace water-distribution system were listed, and a definitive exposure timeframe was identified for the period 1982–1985. The period 1954–1982 was identified as an unknown exposure time frame (ATSDR 1997).

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Base from U.S. Marine Corps and U.S. Geological Survey digital data files



Base from U.S. Marine Corps and U.S. Geological Survey digital data files

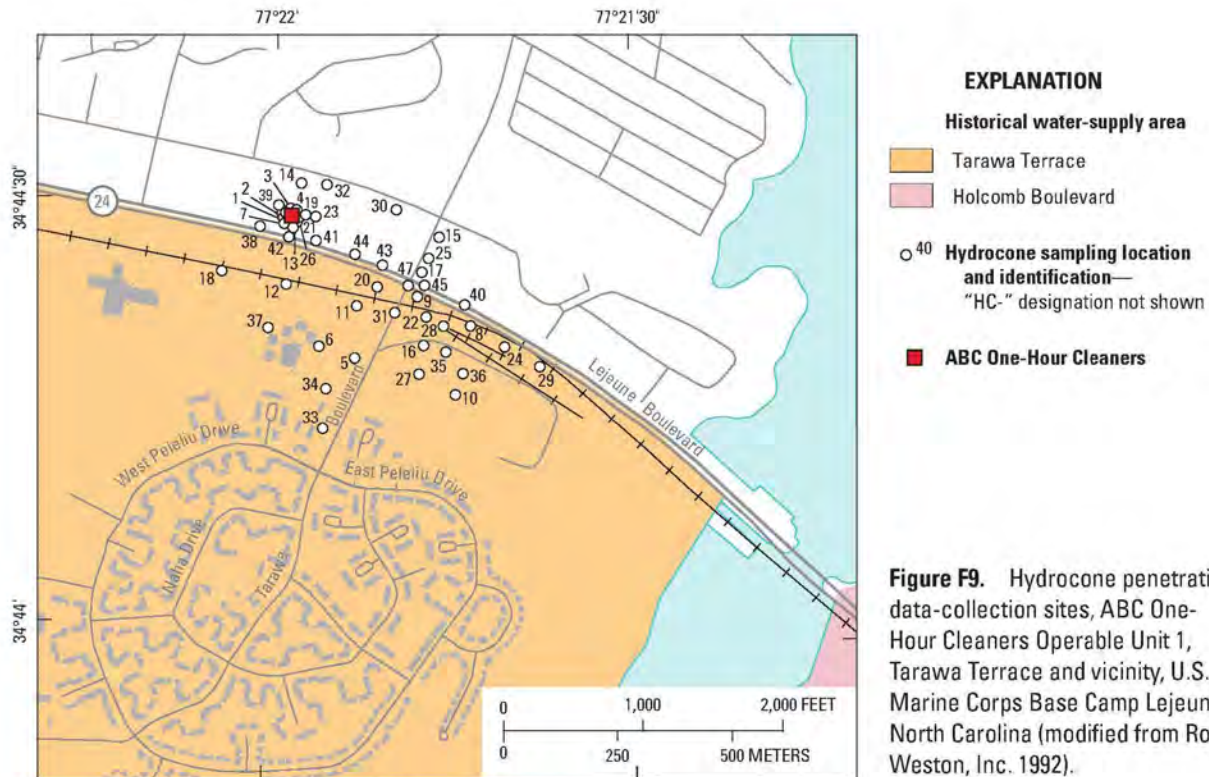


Figure F9. Hydrocone penetration data-collection sites, ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina (modified from Roy F. Weston, Inc. 1992).

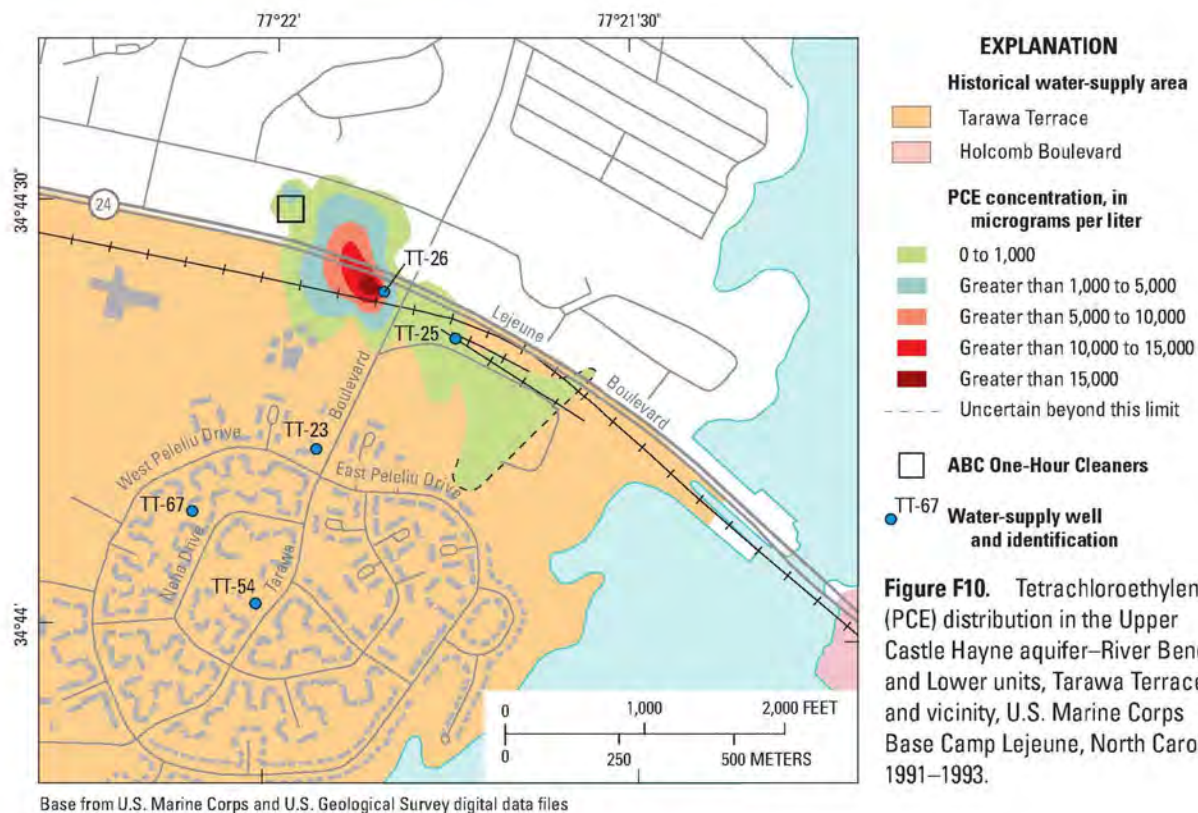


Figure F10. Tetrachloroethylene (PCE) distribution in the Upper Castle Hayne aquifer—River Bend and Lower units, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1991–1993.

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Table F7. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at hydrocone penetration sites during ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 15, 1991.

[µg/L, microgram per liter; ND, not detected; —, constituent not determined; J, estimated value; unless noted by superscript "2," detection limit is unknown]

Site name ¹	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L	Site name ¹	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
HC-1-17.5	4	ND	—	HC-17-24	ND	ND	—
HC-1-39	1.7	ND	—	HC-17-24	² ND	² ND	² ND
HC-2-21.5	1.5J	0.13J	—	HC-17-44	ND	ND	—
HC-2-44.5	5	ND	—	HC-17-44	² ND	² ND	² ND
HC-3-21	2.5J	ND	—	HC-18-24	1J	ND	—
HC-3-40.5	ND	ND	—	HC-18-36	ND	ND	—
HC-4-19	ND	ND	—	HC-18-36	² ND	² ND	² ND
HC-4-40	0.16J	ND	—	HC-19-25	53.3	ND	—
HC-5-25	0.38J	ND	—	HC-19-35.5	157	ND	—
HC-5-25	2J	ND	ND	HC-19-35.5	² 200	² 100	² 170
HC-5-42.5	ND	ND	—	HC-20-34	500	ND	—
HC-6-30	5	ND	—	HC-20-34	² 30,000	² 2,900	² 5,700
HC-6-41	9.4	ND	—	HC-20-41	196	ND	—
HC-6-64	0.6J	ND	—	HC-20-41	² 43	² 29	² 89
HC-7-26.5	0.93J	ND	—	HC-21-22	96	ND	—
HC-7-26.5A	² 4	² ND	² ND	HC-21-22	² 6,900	² 1,100	² 2,300
HC-7-39	8.1	ND	—	HC-21-31.5	13.5	ND	—
HC-7-39	² 2J	² ND	—	HC-22A-30	740	ND	—
HC-8-28	5	ND	—	HC-22-41	5.2	ND	—
HC-8-35	6.8	ND	—	HC-23-19	2.2J	ND	—
HC-8-35	² 27	² 3J	² ND	HC-23-45	11	ND	—
HC-9-31	175.7	ND	—	HC-24-28	14	ND	—
HC-9-36.5	6.3	ND	—	HC-24-38	13	ND	—
HC-10-24	2.5J	ND	—	HC-25-18	8.2	ND	—
HC-10-40	0.8J	ND	—	HC-25-27	6	ND	—
HC-10-40	² ND	² ND	² ND	HC-26-42	5	ND	—
HC-11-24	12.2	ND	—	HC-27-27	4	ND	—
HC-11-34	2.8J	ND	—	HC-27-37.5	3.2	0.34J	—
HC-11-34	² 8J	² ND	² ND	HC-28-28	2.7J	ND	—
HC-12-24	ND	ND	—	HC-28-41	2.2J	ND	—
HC-12-24	² ND	² ND	² ND	HC-29-23	1.4J	ND	—
HC-12-40	3.4J	ND	—	HC-29-26.5	5	ND	—
HC-13-19.5	0.76J	0.19J	—	HC-30-24	2	0.2	—
HC-13-19.5	² 2J	² ND	² ND	HC-30-40	2J	ND	—
HC-13-32	0.4J	ND	—	HC-31-29	1.2J	ND	—
HC-14-20	0.22J	ND	—	HC-31-39	1.4J	ND	—
HC-14-20	² ND	² ND	² ND	HC-32-26	1.3J	ND	—
HC-14-40	ND	ND	—	HC-32-38	1.1J	ND	—
HC-14-40	² ND	² ND	² ND	HC-33-28	2J	ND	—
HC-15-24	ND	ND	—	HC-33-36	1.5J	ND	—
HC-15-24	² ND	² ND	² ND	HC-34-21.5	2J	0.3J	—
HC-15-36.5	ND	2.8J	—	HC-34-34	2J	ND	—
HC-15-36.5	² ND	² ND	² ND	HC-35-30	133	ND	—
HC-16-30	0.23J	ND	—	HC-35-42	7.5	ND	—

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Table F7. Summary of selected analyses for tetrachloroethylene (PCE), trichloroethylene (TCE), and *trans*-1,2-dichloroethylene (1,2-tDCE) in water samples collected at hydrocone penetration sites during ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 15, 1991.—Continued

[µg/L, microgram per liter; —, constituent not determined; J, estimated value; ND, not detected; unless noted by superscript "2," detection limit is unknown]

Site name ¹	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L	Site name ¹	PCE concentration, in µg/L	TCE concentration, in µg/L	1,2-tDCE concentration, in µg/L
HC-36-30	ND	ND	—	HC-42-24	ND	ND	—
HC-36-30	² ND	² ND	² ND	HC-42-40	ND	ND	—
HC-36-41	1J	ND	—	HC-43-24	33	ND	—
HC-37-27	0.3J	ND	—	HC-43-34	1,060	ND	—
HC-37-48	1.4J	ND	—	HC-44-28	6	ND	—
HC-38-24	0.5J	ND	—	HC-44-28	² 13	² 5J	² 17
HC-38-40	1.2J	ND	—	HC-44-39	12,860	ND	—
HC-39-23	0.9J	ND	—	HC-45-28	ND	ND	—
HC-39-23	² ND	² ND	² ND	HC-45-38	² J	ND	—
HC-39-35	2.4J	ND	—	HC-47-26	18	ND	—
HC-40-26	ND	ND	—	HC-47-38	30	ND	—
HC-40-40	ND	ND	—				
HC-41-27	82	ND	—				
HC-41-27	² 120	² 4J	² 4J				
HC-41-45	2J	ND	—				

¹See Figure F9 for location²Detection limit = 10 µg/L

Site name key: Example HC-20-34
 HC Hydrocone site
 20 Site location number
 34 Sample depth

Table F8. Location coordinates of hydrocone penetration sites, ABC One-Hour Cleaners Operable Unit 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

Site name ¹	Location coordinates ²	
	North	East
HC-1	364830	2490670
HC-2	364980	2490675
HC-3	365020	2490700
HC-4	365010	2490750
HC-5	363870	2491230
HC-6	363850	2490960
HC-7	364800	2490680
HC-8	364080	2492020
HC-9	364310	2491690
HC-10	363604	2491940
HC-11	364250	2491230
HC-12	364350	2490730
HC-13	364790	2490730
HC-14	365050	2490810
HC-15	364740	2491810
HC-16	363946	2491690
HC-17	364470	2491670
HC-18	364410	2490280
HC-19	364975	2490850
HC-20	364370	2491372
HC-21	364970	2490770
HC-22	364130	2491710
HC-23	364960	2490910
HC-24	363960	2492270

Site name ¹	Location coordinates ²	
	North	East
HC-25	364590	2491750
HC-26	364820	2490750
HC-27	363738	2491680
HC-28	363080	2491836
HC-29	363810	2492550
HC-30	364950	2491520
HC-31	364170	2491510
HC-32	365060	2490980
HC-33	363365	2491045
HC-34	363640	2491090
HC-35	363884	2491860
HC-36	363756	2491996
HC-37	364050	2490590
HC-38	364770	2490550
HC-39	365040	2490650
HC-40	364250	2492010
HC-41	364700	2490920
HC-42	364720	2490730
HC-43	364500	2491410
HC-44	364610	2491200
HC-45	364390	2491730
HC-47	364400	2491600

¹See Figure F9 for location²Location coordinates are North Carolina State Plane coordinates, North American Datum of 1983

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Table F9. Construction data for Tarawa Terrace water-supply wells, test well T-9, and Civilian Conservation Corps well CCC-1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[NGVD 29, National Geodetic Vertical Datum of 1929; N/A, data not available; AKA, also known as; >, greater than]

Site name	Land-surface altitude, in feet above NGVD 29	Completion date	Borehole depth, in feet	Well depth, in feet	Screen diameter, in inches	Open interval, in feet below land surface
¹ 2A	26	5/24/1951	130	130	8	93–130
² #6	22	1951(?)	N/A	150–200(?)	N/A	N/A
² #7	24	1951(?)	N/A	150–200(?)	N/A	N/A
¹ CCC-1	24.3	9/17/1941	105	75	10	52–75
¹ T-9	28.7	3/1959	202	88	8	37–42 50–60 68–72 83–88
³ TT-23	23.9	3/14/1983	263	147	10	70–95 132–42
³ TT-25	32.0	7/9/1981	200	180	8	70–75 85–95 150–75
³ TT-26, AKA #1	34.0	5/18/1951	180	108	8	91–108
³ TT-27, AKA #2B	26.4	5/31/1951	90	90	10	77–90
³ TT-28, AKA #3	26	1951	N/A	50–100(?)	N/A	N/A
³ TT-29, AKA #4	25	1951	N/A	50–100(?)	N/A	N/A
³ TT-30, AKA #13	26	1971	N/A	128	N/A	50–70 98–113
³ TT-31, AKA #14	25.8	1973	N/A	94	N/A	N/A
³ TT-45, AKA #5	26	1951	N/A	50–100(?)	N/A	N/A
³ TT-52, AKA #9	24.9	6/27/1961	102	98	N/A	N/A ⁴
³ TT-53, AKA #10	25	7/22/1961	N/A	90	10	42–62 68–83
³ TT-54, AKA #11	22.1	6/30/1961	N/A	104	N/A	N/A ⁴
³ TT-55, AKA #8	26.4	11/1/1961	N/A	>50	N/A	N/A ⁴
³ TT-67, AKA #12	27.5	11/15/1971	200	104	8	70–94

¹See Plate 1, Chapter A report, for location (Maslia et al. 2007)²Out of map area, location not shown. North Carolina State Plane coordinates: #6 (highly approximate) North 369730, East 2481720; #7 (highly approximate) North 370500, East 2481530; and TT-45 North 365688, East 2483352³See Figure 1 for location⁴Construction is probably similar to TT-53

Table F10. Construction data for monitor wells installed during ABC One-Hour Cleaners Operable Units 1 and 2 and by the North Carolina Department of Natural Resources and Community Development, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[NGVD 29, National Geodetic Vertical Datum of 1929]

Site name ¹	Land-surface altitude, in feet above NGVD 29	Completion date	Borehole depth, in feet	Well depth, in feet	Screen diameter, in inches	Open interval, in feet below land surface
C1	30.6	4/4/1992	104.0	100.6	4	90–100
C2	32.0	4/8/1992	87.0	85	4	74.5–84.5
C3	33.4	4/9/1992	90.5	90.5	4	79.1–89.1
C4	32.2	4/2/1992	200.0	130.4	4	120–130
C5	32.0	4/7/1992	92.5	91	4	80.5–90.5
C9	32.1	9/1993	76	76	4	66–76
C10	32.5	10/1993	175	175	4	165–175
C11	31.0	9/1993	108	108	4	98–108
PZ-01	31.9	9/1993	80	80	2	74.5–79.5
PZ-02	31.9	9/1993	35	35	2	29.5–34.5
PZ-03	32.5	9/1993	80	80	2	74.5–79.5
PZ-04	32.5	9/1993	35	35	2	29.5–34.5
PZ-05	32.0	9/1993	80	80	2	74.5–79.5
PZ-06	32.0	9/1993	35	35	2	29.5–34.5
S1	30.6	3/22/1992	28.0	25.5	4	5.5–25.5
S2	32.5	3/26/1992	39.7	39.7	4	19.7–39.7
S3	33.4	4/2/1992	39.5	39.5	4	19.5–39.5
S4	32.2	4/3/1992	34.0	34	4	14–34
S5	31.9	4/1/1992	30.0	28	4	8–28
S6	31.1	3/26/1992	40.5	40.5	4	20.5–40.5
S7	31.3	4/5/1992	30.3	30.3	4	10–30
S8	30.8	4/4/1992	28.0	28	4	8–28
S9	32.7	3/21/1992	40.0	28.3	4	8–28
S10	31.6	3/19/1992	40.0	35	4	15–35
S11	30.8	9/1993	35	35	4	15–35
² X24B4	33.3	9/25/1985	59	59	2	42–52
² X24B5	31.4	9/25/1985	59	59	2	42–52
² X24B6	33.4	9/25/1985	59	59	2	42–52

¹See Figure F6 for location

²See Plate 1, Chapter A report, for location (Maslia et al. 2007). X24B4, X24B5, and X24B6 are shown as B4, B5, and B6, respectively

Conceptual Model of Groundwater Flow

Conceptual Model of Groundwater Flow

A conceptual model of groundwater-flow directions and budget quantities is a necessary element of flow-model development and calibration. The source of water to the Tarawa Terrace and underlying aquifers in the study area is recharge from precipitation. Recharge to the Castle Hayne aquifer system occurs originally as infiltration of precipitation to the water table. Average annual effective recharge, defined herein as recharge to the water table remaining after discharge to evapotranspiration, is described in previous investigations as ranging from about 11 to about 19 inches per year (in/yr) in the study area (LeGrand 1959; Heath 1994; Giese and others 1997; Baker Environmental, Inc. 1998). These rates conform well to maps of average annual rainfall and annual potential evaporation by Heath (1994, Figures 9 and 12), which indicate rates from about 56 to 60 in/yr and 42 in/yr, respectively, for Onslow County. Within the study area (Figure F1), surface soils generally are sands or silty sands, and the land surface largely is undissected by streams, indicating little or minimal runoff. Thus, long-term, average annual effective recharge rates in the study area could be as much as 18 in/yr, the maximum difference between rates of average annual rainfall and annual potential evaporation (Heath 1994, Figures 9 and 12).

The spatial configuration of the water table prior to development of local aquifers by wells probably resembled, to a large degree, a subdued replica of surface topography (Figure F1). Consequently, precipitation recharged to the water table flowed laterally from highland to lowland areas and eventually discharged to surface-water bodies. Northeast Creek and New River are partially or completely incised within the Tarawa Terrace aquifer and Upper Castle Hayne aquifer–River Bend unit and receive water directly from these aquifers. Frenchmans Creek, near the western limit of the study area, is apparently a perennial stream through most of its reach and probably also derives baseflow directly from the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer–River Bend unit.

Lateral flow directions within the Upper, Middle, and Lower Castle Hayne aquifers probably mimic, to a large degree, corresponding directions within the Upper Castle Hayne aquifer–River Bend unit, except in the immediate vicinity of discharge areas such as Northeast Creek and New River, where flow directions within the deeper confined aquifers are vertically upward. Diffuse vertical leakage across confining units and between aquifers probably is pronounced in the vicinity of pumping wells, where vertical hydraulic gradients are relatively large, but is limited elsewhere by small vertical head gradients and the thickness and vertical hydraulic conductivity of confining units. Groundwater probably flows vertically downward through the Upper and Middle Castle Hayne aquifers in areas of recharge in the northern part of the study area near and somewhat south of Lejeune Boulevard (SR 24) and probably is vertically upward within these same aquifers in the vicinity of New River and Northeast Creek. Paired observations that measure water levels in individual aquifers of the Castle Hayne aquifer system are not available

for the study area; however, long-term measurements are available for the Upper and Lower Castle Hayne aquifers at site X24S located just north of Wallace Creek (Plate 1). These data are possibly influenced by local pumping but indicate less than a 3-ft head difference occurred between the Upper and Lower Castle Hayne aquifers during 1987–2004. The head gradient was vertically upward (North Carolina Division of Water Resources, written communication, August 30, 2005). Similar flow conditions probably occurred within the study area during the period of interest to this investigation in the vicinities of Northeast Creek and New River.

Following the onset of pumping at water-supply wells during 1952, groundwater flow that under predevelopment conditions was entirely directed toward Northeast Creek, New River, and Frenchmans Creek was partially diverted to pumping wells. Consequently, (1) predevelopment potentiometric levels near and in the vicinity of pumping wells declined in the aquifers open to the wells, (2) predevelopment flow directions changed preferentially toward wells from natural points of discharge such as Northeast Creek, and (3) potentiometric levels possibly declined near groundwater/topographic divides resulting in the migration of boundaries farther west or north of predevelopment locations. Water-level declines near or in the vicinity of Northeast Creek or New River possibly caused a complete reversal in the direction of groundwater flow such that saltwater or brackish water from these surface-water bodies intruded landward into the Tarawa Terrace or Upper Castle Hayne aquifers.

Conceptual Model of Tetrachloroethylene (PCE) Migration

Migration of PCE to the water table in the immediate vicinity of ABC One-Hour Cleaners and subsequently to Tarawa Terrace water-supply wells probably began with the onset of dry-cleaning operations during 1953. The floor drain used to discharge waste streams and spillage from ABC One-Hour Cleaners was apparently in place at this time as was the septic tank–soil absorption system that received the drain discharge. The septic tank–soil absorption system also was connected to and was used by several other businesses proximate to ABC One-Hour Cleaners (Hopf & Higley, P.A., Deposition of Victor John Melts, written communication, April 12, 2001). The drain laterals and drain field related to the septic tank–soil absorption system were probably located to the rear of ABC One-Hour Cleaners but were never traced during ABC One-Hour Cleaners Operable Unit 2. Neither the depth nor length of drain laterals was determined (Roy F. Weston, Inc. 1994). However, the sandy soils noted in soil boring logs obtained in the immediate vicinity of ABC One-Hour Cleaners (Roy F. Weston, Inc. 1994) probably are characterized by a relatively high infiltration capacity, and drain laterals were probably placed between 5 and 10 ft below ground level. Waste streams discharged to the septic tank–soil absorption system were probably composed mostly of water, by volume,

Conceptual Model of Tetrachloroethylene (PCE) Migration

in substantially larger quantities than corresponding discharges of PCE mass. Accordingly, PCE concentrations in the mixed waste streams were probably always below solubility limits (150 mg/L), and PCE occurred in solution in the subsurface, rather than as “pure product.”

Once discharged to the drain field, wastewater containing PCE and PCE spillage in solution migrated downward through the unsaturated zone to the water table or was lost to evapotranspiration in the immediate vicinity of the drain field. Thickness of the unsaturated zone in the vicinity of ABC One-Hour Cleaners ranges from about 20 to 25 ft, and the water table probably fluctuates seasonally across a range of 2 or 3 ft (Roy F. Weston, Inc. 1992, 1994; Harned and others 1989). Analyses of core samples collected during ABC One-Hour Cleaners Operable Units 1 and 2 at numerous locations surrounding ABC One-Hour Cleaners (Figure F5) indicated PCE occurrences to a depth of 14 or 15 ft at several sites. Concentrations ranged to 580,000 mg/kg west of and adjacent to the septic tank. The maximum concentration noted in these core samples of 2,100,000 mg/kg occurred at a depth range from 0 to 2 ft in the alley east of the building housing ABC One-Hour Cleaners and may have been the result of “still bottom” disposal practices. Samples were collected during 1992 and 1993 (Roy F. Weston, Inc. 1994, Figure 5-2).

At the water table, the wastewater stream containing the PCE mass mixed with groundwater, and PCE was transported advectively along potentiometric gradients and by diffusion along declining concentration gradients. Transport velocity under each condition was dependent on the magnitude of the respective gradients and, with respect to advection, the lateral and vertical hydraulic conductivities of the Tarawa Terrace aquifer and the Upper Castle Hayne aquifer–River Bend unit. Lateral potentiometric contours within the Upper Castle Hayne aquifer–River Bend unit during June 1992 are shown in Figure F7 and correspond to gradients ranging from about 0.005 to 0.007 ft/ft to the southeast (Roy F. Weston, Inc. 1992, Figure 4-6). Such gradients probably closely resemble predevelopment conditions as groundwater pumping at Tarawa Terrace was terminated during March or April 1987. Note that groundwater-flow directions and, thus, lateral advection is southeast toward Tarawa Terrace water-supply wells TT-25 and TT-26 and Northeast Creek (Figure F1). Vertical head gradients within the Upper Castle Hayne aquifer in the vicinity of ABC One-Hour Cleaners were small but generally downward during 1992 and 1993 (Roy F. Weston, Inc. 1992, 1994), and PCE probably was transported downward along these gradients. However, lateral advection was probably the primary mechanism of PCE transport in groundwater at Tarawa Terrace and vicinity.

The onset of pumping at Tarawa Terrace water-supply wells during 1952 substantially increased lateral and vertical groundwater-flow gradients in the vicinity of ABC One-Hour Cleaners compared to natural gradients (Figures F7 and F8). Such changes increased lateral and downward groundwater-flow velocities and, hence, advective transport velocities, and preferentially altered flow and PCE transport directions

toward the pumping wells. Water-supply well TT-26 began operation during 1952 and was located along a direct groundwater flowpath from ABC One-Hour Cleaners. The proximity of this well to the source of PCE (about 900 ft), its relatively shallow construction (Table F9), and its location with respect to preferential groundwater-flow directions indicate that the first occurrence of PCE breakthrough at a Tarawa Terrace water-supply well probably occurred at well TT-26. Nearby water-supply well TT-25 was located about 1,400 ft southeast from ABC One-Hour Cleaners (Figure F1) and began operation during 1981. The location and relatively shallow open intervals of this well indicate possible breakthroughs of PCE and related degradation products also occurred at this site following the onset of pumping. Four water-supply wells were located northwest of ABC One-Hour Cleaners and probably also began operation during 1952 (TT-27, TT-28, TT-29, and TT-45). The discharge of these wells during their period of operation was limited to about 100 gallons per minute (gal/min) or less (LeGrand 1959), and their limited radius of influence combined with their location upstream of the PCE source probably minimized or eliminated the possibility of PCE breakthrough at these sites. Water-supply well TT-55 began operation about 1961 and was located near well TT-27. Construction information regarding this well is not available; however, construction was probably similar to that reported for water-supply well TT-53. Water-supply well TT-30 began operation during 1972 and was located near well TT-28. Considerations of a location upstream of the PCE source and a limited radius of influence described for wells TT-27 and TT-28 probably also applied to wells TT-30 and TT-55, and any breakthrough of PCE or related degradation products was probably minimal or did not occur at all at these sites. Water-supply wells generally south of ABC One-Hour Cleaners and located within the Tarawa Terrace housing areas included, in order of year of beginning operation, TT-52 (1962), TT-53 (1962), TT-54 (1962), TT-67 (1972), TT-31 (1973), and TT-23 (1984). The most proximate of these wells to ABC One-Hour Cleaners was TT-23, at a distance of about 1,700 ft. The farthest of these wells from ABC One-Hour Cleaners was TT-31 at a distance of about 3,000 ft. With the exception of well TT-23, all of these wells were in operation for a minimum of 12 years prior to the termination of operations at wells TT-23 and TT-26. Because of their proximity to one another and similar depth, cones of depression created by pumping at individual wells from the same water-bearing units possibly coalesced and created a large single cone of depression when three or more of these wells were operating at the same time. Drawdown related to this large single cone of depression was probably most extreme in the Upper Castle Hayne aquifer–River Bend and Lower units, the same units open to well TT-26, and possibly caused groundwater to flow generally south from the direction of ABC One-Hour Cleaners toward Tarawa Terrace housing. Accordingly, PCE probably migrated south and was available in sufficient quantities in the vicinity of well TT-23 to contaminate the water supply at the onset of operations at this well during 1984.

Simulation of Tetrachloroethylene (PCE) Migration

In addition to dilution and diffusion, PCE concentrations during migration were altered by (1) adsorption onto soil particles, particularly silts and clays, (2) degradation by biological processes sequentially into TCE, DCE, and finally vinyl chloride, and (3) dispersion. Biodegradation is the only one of these processes actually observed at Tarawa Terrace and vicinity and had occurred completely at water-supply well TT-26 by January 1985, about 1 month prior to the termination of well operations because of contamination. The reported concentrations of PCE, TCE, DCE, and vinyl chloride at TT-26 at this time were, respectively, 1,580, 57, 92, and 27 $\mu\text{g/L}$ (Shiver 1985). The DCE concentration was reported as the isomer 1,2-tDCE. Biodegradation of PCE in the unsaturated zone in the immediate vicinity of ABC One-Hour Cleaners also was noted in soil cores during 1992 (Roy F. Weston, Inc. 1992, Table 2-4). Concentrations of TCE in 22 core samples from 10 individual boreholes ranged from about 0.1 to 860 mg/kg. Concentrations of 1,2-dichloroethylene in every sample were less than 0.1 mg/kg. These data indicate that the vicinity of ABC One-Hour Cleaners probably also was a source of TCE to groundwater.

Simulation of Tetrachloroethylene (PCE) Migration

The original version of the numerical code used in this study to simulate groundwater flow was written by McDonald and Harbaugh (1984) and was designated a modular finite-difference groundwater-flow model (MODFLOW). The code used to simulate contaminant transport is designated MT3DMS, version 4, written by Zheng and Wang (1998).

The MODFLOW code simulates groundwater flow in a three-dimensional heterogeneous and anisotropic porous medium. Updates to the original MODFLOW code were developed periodically along with various modules to expand simulation capability and computational performance. The MT3DMS code is a modular, three-dimensional transport model that simulates advection, dispersion, and chemical reactions of contaminants in groundwater. The MODFLOW version used in this study is known as MODFLOW 96 (Harbaugh and McDonald 1996). The MT3DMS code used is version 4.00. Both codes are part of a highly integrated simulation system called PMWINPro (Processing MODFLOW Pro, version 7.017), which also includes codes that support and augment groundwater-flow and transport simulation using techniques such as particle tracking and inverse modeling (Chiang and Kinzelbach 2001). The capability to simulate advective transport also is integrated within PMWINPro and is based on techniques and codes first published by Pollock (1989, 1994). Two flow models were calibrated: (1) a predevelopment flow model representing long-term average, steady-state groundwater-flow conditions prior to the development of the Castle Hayne aquifer system and (2) a transient flow model representing pumping of the Castle Hayne aquifer system as a water supply for Tarawa Terrace. The transient flow model was subdivided into 528 stress periods, representing monthly conditions beginning

during January 1951 and ending during December 1994 (Appendix F1). A single month corresponded to a single stress period, and each stress period represented a single time step. The unit of time was days. Thus, the appropriate number of days representing a particular month was assigned as the time interval of the stress period. The fate and transport model, the subject of this report, was linked directly to the transient flow model with an equivalent time unit (days), equal stress periods (months), and equal time discretization within stress periods. The active model domain, model grid, model boundary conditions, model geometry, hydraulic characteristic arrays, pumpage arrays, recharge arrays, and all other model elements common to the calibrated predevelopment flow model, transient flow model, and fate and transport model were identical. The model domain and geometry are briefly described in the following section. All flow model arrays and flow model calibrations are described in detail in Faye and Valenzuela (2007).

Model Domain and Boundary Conditions

The total domain of the Tarawa Terrace groundwater-flow and fate and transport models comprises most of the area north and west of the mid-channel line of Northeast Creek. The total area represented by the model domain is shown in Figure F11. For modeling purposes, the total domain was subdivided into active and inactive domains. The active domain, which corresponds to the area pertinent to the simulation of groundwater flow and PCE fate and transport, is the blue gridded area shown in Figure F11, and also includes the adjacent dark blue area that extends to the mid-channel of Northeast Creek. The remaining area within the total model domain but outside the gridded area is the inactive domain. The total model domain was subdivided into 270 columns and 200 rows of square cells representing a length of 50 ft per side ($\Delta x = \Delta y = 50$ ft). The model was subdivided vertically into seven layers. Model layer 1 corresponds to the combined Tarawa Terrace aquifer, the Tarawa Terrace confining unit, and the Upper Castle Hayne aquifer–River Bend unit (Table F1). The remaining six layers correspond, respectively, to the Local confining unit, the Upper Castle Hayne aquifer–Lower unit, the Middle Castle Hayne confining unit, the Middle Castle Hayne aquifer, the Lower Castle Hayne confining unit, and the Lower Castle Hayne aquifer. The area represented by the total model domain is about 135,000 square feet (ft^2) or about 4.8 square miles (mi^2). The active model domain corresponds to an area of about 59,400,000 ft^2 , about 2.1 mi^2 or about 1,360 acres. Model layer 1 was specified as an unconfined aquifer and contains the water table. All other model layers were specified as confined.

The base of simulated groundwater flow and PCE mass transport corresponds to the top of the Beaufort confining unit and is implicitly a no-flow boundary. Boundaries assigned to the eastern, western, southwestern, and southern perimeters of the active model domain were all no-flow and are equal in location and condition for each layer. The southern boundary and most of the eastern boundary conform to the mid-channel line of Northeast Creek. The western boundary conforms to

Simulation of Tetrachloroethylene (PCE) Migration

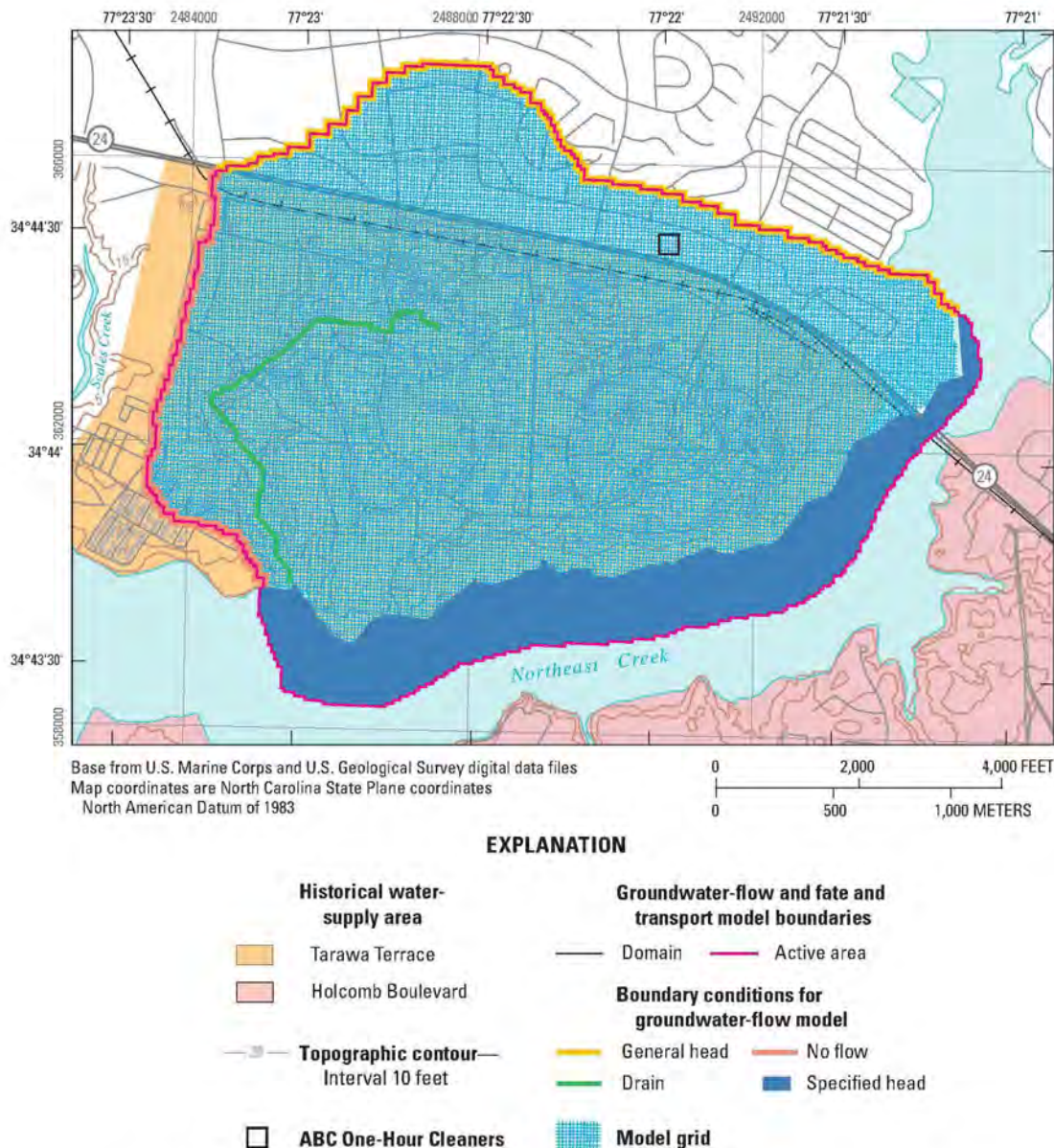


Figure F11. Groundwater-flow model grid and model boundaries, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

the topographic divide that separates the drainage areas of Scales and Frenchmans Creeks (Figure F1). The northern boundary also generally conforms to a topographic divide but was assigned as a general-head (head-dependent) boundary in all model layers because of the proximity of water-supply wells to the boundary in the northeastern and north-central parts of the active model domain (Figures F1 and F11). The surface of Northeast Creek within the active domain was assigned a specified head of zero in model layer 1, corresponding to sea level. A drain also was assigned to model layer 1 along the channel of Frenchmans Creek in the western part of the model area. Drain altitudes were interpolated to the center

of drain cells using detailed topographic maps and ranged from zero to about 16 ft.

Boundaries assigned exclusively to the fate and transport model were (1) a mass loading rate for PCE of 1,200 grams per day (g/d) applied to the model cell that corresponds to layer 1, row 47, column 170; and (2) a no-contaminant flux boundary along the eastern, western, southern, and northern perimeters of the active model domain. Mass loading occurred continuously from stress period 26 (January 1953) to stress period 408 (December 1984). Prior to stress period 25 and after stress period 408, the assigned mass loading rate was 0.0 g/d.

Simulation of Tetrachloroethylene (PCE) Migration

Model Input Data and Initial Conditions

Other than advection, the subsurface fate and transport of PCE at Tarawa Terrace and vicinity probably was most affected by the various hydrodynamic, geochemical, and biological processes that relate, respectively, to dispersion, sorption, and biodegradation. Accordingly, simulation of PCE migration using MT3DMS required a variety of input data descriptive of these processes. Dispersion was accounted for using assigned dispersivities parallel to the longitudinal, transverse, and vertical-flow directions. Longitudinal dispersivity is in the principal direction of flow. Transverse dispersivity is orthogonal to and generally smaller than longitudinal dispersivity. Longitudinal dispersivity was assigned to MT3DMS as an array. Transverse and vertical dispersivities were computed as ratios or percentages of longitudinal dispersivity. Sorption was probably the primary geochemical process affecting PCE migration. Sorption processes are commonly determined using results of sorption equilibrium experiments conducted in laboratory columns using soil samples obtained from the area or areas of interest and solutes representative of actual or presumed subsurface contaminants. The net effect of all sorption processes is the removal of solute, in this case PCE, from solution to the porous media. Neither laboratory nor field-scale estimates of PCE dispersivity or sorption unique to the Tarawa Terrace area were available for this study, and initial estimates of these parameters were obtained from literature sources. A first-order rate of biodegradation of PCE was computed using concentration data listed in Table F2 and was applied as an initial condition to the MT3DMS model. Detailed discussions of these and related model input parameters are provided in the following sections.

Hydrodynamic Dispersion

To compute directional values of the hydrodynamic dispersion coefficients, MT3DMS requires the cell-by-cell assignment of the effective molecular diffusion coefficient for PCE in water, longitudinal dispersivity, and the ratios of transverse and vertical dispersivity to longitudinal dispersivity. Coefficients of molecular diffusion of PCE as a solute in water examined for this study ranged from 7.0×10^{-4} square feet per day (ft^2/d) (Lucius and others 1990) to 9.5×10^{-4} ft^2/d (California Environmental Protection Agency 1994). A mid-range value of 8.5×10^{-4} ft^2/d was assigned to all model layers for all stress periods for this study and was not varied during model calibration.

Estimates of longitudinal dispersivity were obtained from a variety of sources. Anderson (1984, Figure 2.4) and Fetter (1999, Figure 2.17) show a graph originally published by Lallemant-Barrès and Peaudecerf (1978) indicating that field-scale or longitudinal dispersivity is about one-tenth of a characteristic length or apparent length scale. Neuman (1990) extended the work of Lallemant-Barrès and Peaudecerf and others to derive a universal scaling rule. Neuman related longitudinal dispersivity to scales of investigation within a variety of porous media under diverse conditions of groundwater flow and solute transport. Data were derived from laboratory and field-scale investigations. The most general equation derived

by Neuman (1990) using 131 of 134 possible data pairs and representing a large range of scales of investigation is

$$\alpha_L = 0.0175L_s^{1.46} \quad (1)$$

where,

α_L = longitudinal macrodispersivity, and
 L_s = a characteristic or apparent scale length.

The characteristic length or scale length is unique to the distribution of hydraulic conductivity within a particular aquifer or groundwater-flow regime and is commonly defined as the minimum length of groundwater flowpaths at which all possible variations in hydraulic conductivity are encountered by migrating solutes (paraphrased from Fetter 1999, p. 84). The characteristic length is apparently also proportional to aquifer heterogeneity and anisotropy.

The characteristic length of aquifers at Tarawa Terrace and vicinity is unknown. However, boring logs of the Tarawa Terrace and Upper Castle Hayne aquifers collected at Tarawa Terrace (Roy F. Weston, Inc. 1992, 1994) indicate that fine sands, which compose the vast majority of aquifer sediments, are uniform to highly uniform. A particle-size distribution of a single composite sample of sand collected from the Tarawa Terrace aquifer at Tarawa Terrace indicated a uniformity coefficient of about 1.6 (Miller et al. 1989). Uniformity also is indicated by the results of aquifer tests reported in Faye and Valenzuela (2007, Tables C2–C4), wherein horizontal hydraulic conductivity determined from 13 tests conducted at wells completed generally in the Upper Castle Hayne aquifer–River Bend unit ranged from 10 to 50 ft/d and averaged 22 ft/d. Standard deviation of these test results was 11 ft/d. The horizontal hydraulic conductivity determined from 14 tests conducted at wells largely open to the Upper Castle Hayne aquifer–River Bend and Lower units ranged from 8 to 40 ft/d and averaged 18 ft/d. Standard deviation of these test results was 10 ft/d. Such results indicate that substantial macro- or field-scale hydraulic heterogeneities probably do not occur within the Tarawa Terrace and Upper Castle Hayne aquifers within the study area and the heterogeneities that are present are probably statistically homogeneous on a scale equal to or smaller than the scale of investigation (Neuman 1990). With respect to aquifer tests, the scale of investigation corresponds to distances equal to or less than the radius of influence of the pumped well, which at Tarawa Terrace water-supply wells probably equals several hundred feet.

Longitudinal dispersivity applied to numerical model codes based on finite-difference methods, such as MODFLOW and MT3DMS, also is dependent on the scale of the model. Model scale is commonly represented by cell size and grid discretization. Discretization of the Tarawa Terrace MODFLOW and MT3DMS models is uniform. Thus, cell dimensions (50 ft by 50 ft) determine the scale of investigation and the approximate order of magnitude of longitudinal dispersivity. Assigning a hypothetical longitudinal dispersivity of 50 ft to Equation 1 yields a characteristic length of about 230 ft, which approximates the combined length of 5 model cells (250 ft). Gelhar et al. (1992) published several scatter diagrams, similar to those of Neuman (1990), comparing longitudinal

dispersivity to observation scale. At a given scale, the longitudinal dispersivity values ranged across 2 to 3 orders of magnitude. Data within the lower part of a range were described as probably the most reliable (Gelhar et al. 1992, Figure 2). Projecting a measurement scale of 250 ft to the approximate center of the scatter data of Gelhar et al. (1992) corresponds to a longitudinal dispersivity of about 10 meters (about 30 ft). Gelhar et al (1992) also point out that vertical dispersivities are typically an order of magnitude or more smaller than transverse dispersivities and that transverse dispersivities are typically an order of magnitude less than longitudinal dispersivities.

The uniformity of sand particle-size distributions and aquifer-test results indicate that substantial macro-scale hydraulic heterogeneities probably do not occur within the Tarawa Terrace and Upper Castle Hayne aquifers of the study area. Accordingly, a characteristic length for groundwater flowpaths of 250 ft and equal to 5 model cell lengths was initially assigned and used to estimate field-scale longitudinal dispersivity. This characteristic length when combined with the results of Lallemant-Barrès and Peaudecerf (1978) cited previously indicates that a longitudinal dispersivity of about 25 ft is appropriate (0.10×250 ft). The relations between scale length and longitudinal dispersivity described by Neuman (1990) and Gelhar et al. (1992) indicate longitudinal dispersivity values of about 55 and 30 ft, respectively, using a characteristic length of 250 ft. These data provided a magnitude and range of longitudinal dispersivity considered appropriate for calibration of the Tarawa Terrace fate and transport model (25–55 ft). Accordingly, a longitudinal dispersivity of 50 ft was initially assigned uniformly to all layers of the MT3DMS model for all stress periods. The final calibrated longitudinal dispersivity was 25 ft, similarly assigned. Ratios of transverse and vertical dispersivities to longitudinal dispersivity were assigned as 0.1 and 0.01, respectively, to all model layers uniformly for all stress periods and were not varied during calibration.

Sorption

Sorption in MT3DMS is assumed to be an equilibrium-partitioning process between the PCE in solution within the groundwater-flow regime and the sands, clays, and silts that compose the porous media of the aquifers and confining units. Sorption within aquifers and confining units at Tarawa Terrace and vicinity is probably greatly influenced by the fraction of organic matter within the porous media. Boring logs at monitor wells installed during ABC One-Hour Cleaners Operable Units 1 and 2 (Roy F. Weston, Inc. 1992, 1994) qualitatively indicate the occurrence of silt and clay fractions in sediments that compose the Tarawa Terrace and Upper Castle Hayne aquifers. Many of the silts and fine sands are described as gray or black, indicating a relatively high organic composition. Charcoal was noted infrequently at depth. On the other hand, the sand sample collected at Tarawa Terrace from the Tarawa Terrace aquifer and described previously in the context of a particle-size distribution was analyzed for the fraction of organic carbon and cation exchange capacity (Miller et al. 1989). The organic carbon fraction of the sand was small, only

0.024 percent, and the cation exchange capacity was about 5.5 milliequivalents per 100 grams. The intent of the project described by Miller et al. (1989) required the deliberate selection of a sand low in organic material, and the selected sample was probably only partly representative of the Tarawa Terrace aquifer or the Upper Castle Hayne aquifer–River Bend unit.

The MT3DMS code accounts for the sorption process by computing a retardation factor, which is determined by selecting a sorption type: either (1) a linear equilibrium isotherm, (2) a Freundlich nonlinear equilibrium isotherm, or (3) a Langmuir nonlinear equilibrium isotherm. The application of equilibrium isotherms assumes that sorption occurs relatively rapidly in relation to groundwater-flow velocity. Sorption as defined by the linear equilibrium isotherm is possibly the dominant sorption process within the aquifers and confining units of interest to this study. The linear equilibrium isotherm assumes that the sorbed concentration is directly proportional to the dissolved concentration at the model cell and, for modeling purposes, is computationally the most straightforward and efficient of the three isotherm-retardation factor relations accommodated by MT3DMS. The linear equilibrium isotherm also is the least data intensive of the three available sorption types and, accordingly, was the sorption type selected for this study.

The retardation factor is related to the linear equilibrium isotherm by the following formula:

$$R = V_w / V_c = 1 + K_d \rho_b / \theta, \quad (2)$$

where

- R = the retardation factor, dimensionless,
 - K_d = the distribution coefficient, in L^3/M ,
 - ρ_b = the bulk density of the porous media, in M/L^3 ,
 - θ = the effective porosity of the porous media, dimensionless,
 - V_w = linear groundwater velocity, in L/T , and
 - V_c = solute velocity, in L/T .
- (M, L, T = mass, length, time)

The distribution coefficient is the slope of the linear approximation of the equilibrium adsorption isotherm and is unique to a solute and the porous media through which a solute is migrating.

Estimates of retardation factors and distribution coefficients for PCE migration within the Tarawa Terrace aquifer or Castle Hayne aquifer are unknown, and initial estimates applied to the MT3DMS model were based on literature sources. Roberts et al. (1986) reported retardation factors determined from a field-scale investigation of PCE migration through a sand aquifer that ranged from 2.7 to 5.9, based on the collection of high-resolution synoptic data during a period of about 2 years. Retardation factors increased directly with increasing time but at a decreasing rate. Hoffman (1995) reported highly controlled laboratory column determinations of distribution coefficients for PCE migration through gravels, sands, and silt. Of the approximately 150 samples analyzed, the distribution coefficient for sand ranged from 0.25 to 0.76 milliliter per gram (mL/g) and averaged 0.39 mL/g.

Simulation of Tetrachloroethylene (PCE) Migration

Corresponding values for silts ranged from 0.21 to 0.71 mL/g and averaged 0.40 mL/g. Although neither the field-scale experiments reported by Roberts et al. (1986) nor the laboratory results of Hoffman (1995) related to Camp Lejeune or even to North Carolina, the solute investigated in both studies was PCE, and PCE migration was observed through porous media of sand and sands and silts, similar to Camp Lejeune. In addition, the organic carbon content of the porous media selected for the experiments of Hoffman (1995) was less than 0.1 percent, which also is similar to the organic carbon content of sands within part of the Tarawa Terrace aquifer and Upper Castle Hayne aquifer–River Bend unit (Miller et al. 1989). Given these similarities to groundwater conditions at Tarawa Terrace and vicinity, the range of reported retardation factors by Roberts et al. (1986) and distribution coefficients by Hoffman (1995) were considered reasonable initial values for the aquifers and confining units of this study. An initial distribution coefficient of 0.4 mL/g (0.000014 cubic feet per gram [ft³/g]) was applied uniformly to all layers of the MT3DMS model for all stress periods. The final calibrated value was 0.14 mL/g (0.000005 ft³/g), similarly applied. The calibrated retardation factor was 2.9.

The lithology of the Castle Hayne aquifer system and the Tarawa Terrace aquifer and confining unit at Tarawa Terrace and vicinity is characterized by fine silty to clayey sand and sandy to silty clay. The specific gravity of 356 samples of fine sand, as reported by Morris and Johnson (1967), ranged from 2.54 to 2.77 and averaged 2.67. The specific gravity of clay (104 samples) and silt (388 samples) ranged from 2.47 to 2.79 and averaged 2.67 and 2.62, respectively (Morris and Johnson 1967). In addition, two 3-inch undisturbed soil samples collected during soil boring investigations in the vicinity of ABC One-Hour Cleaners were used to determine a variety of geotechnical data including specific gravity and total porosity. The samples were classified as a clayey sand and a silty sand. Specific gravity of the clayey sand was 2.69 and of the silty sand was 2.68. Total porosity of the clayey sand was 32.9 percent; of the silty sand, 36.5 percent (Roy F. Weston, Inc. 1994, Appendix B). Based on these data, a specific gravity of 2.7 was assigned to all sediments represented by the seven layers of the MT3DMS model. Model input requires a conversion of specific gravity to a bulk density. Accordingly a bulk density of sediments of 170 pounds per cubic foot (lbs/ft³) or 77,100 grams per cubic foot (g/ft³) was assigned uniformly to all layers of the MT3DMS model.

The effective porosity of a porous media is that porosity directly related to the volume of connected interstices. Because porosity of unconsolidated sediments is largely primary, effective porosity is probably somewhat to substantially less than total porosity, particularly where silts and clays compose a significant percentage of the media. Effective porosity is closely related to laboratory determinations of specific yield and also is equated with drainage porosity (Brady and Kunkel no date). Published data, primarily Morris and Johnson (1967), were the primary sources of estimates of effective porosity for this study. With respect to fine sand, Morris and Johnson (1967) reported the specific yield of 287 samples ranged from 1 to about

46 percent and averaged 33 percent. Total porosity of fine sand ranged from 26 to about 53 percent and averaged 43 percent, based on the analyses of 243 samples. With respect to silt, total porosity ranged from about 34 to 61 percent and averaged 46 percent, based on the analyses of 281 samples. The specific yield of 266 silt samples ranged from about 1 to 39 percent and averaged 20 percent. The range and average specific yield of 27 clay samples were substantially smaller than corresponding values for fine sand and silt. The specific yield of clay ranged from about 1 to 18 percent and averaged 6 percent. Total porosity of 74 clay samples ranged from about 34 to 57 percent and averaged 42 percent. Drainage porosity of fine sand, reported by Brady and Kunkel (no date) ranged from about 1 to 40 percent and averaged about 19 percent. The average drainage porosity of silt reported by Brady and Kunkel (no date) was about 14 percent and ranged from about 4 to 29 percent.

The primary lithology of the sediments that compose the Castle Hayne aquifer system and the Tarawa Terrace aquifer is fine silty and clayey sand. The mean of the average specific yield values reported for fine sand, silt, and clay by Morris and Johnson (1967) is about 20 percent. This value also closely corresponds to the average drainage porosity of fine sand (about 19 percent) reported by Brady and Kunkel (no date). Accordingly, an effective porosity of 20 percent was initially assigned uniformly to all model layers for all stress periods. The final calibrated effective porosity also was 20 percent, similarly applied.

Biodegradation

Reductions of PCE concentration reported at water-supply well TT-26 between September 1985 and July 1991 (Table F2) probably occurred largely by microbially mediated degradation such as reductive dechlorination. Knowing the initial and final PCE concentrations at well TT-26 for this period and the number of days between measurements, a first-order degradation rate can be computed using the relation

$$C = C_0 e^{-kt}, \quad (3)$$

where

- C = the PCE concentration at well TT-26 on July 11, 1991,
- C₀ = the PCE concentration at well TT-26 on September 25, 1985,
- e = the base of Napierian or Natural logarithms,
- k = the degradation rate constant, in days⁻¹, and
- t = the elapsed time, in days.

The PCE concentrations at water-supply well TT-26 on September 25, 1985, and July 11, 1991, were 1,100 and 350 µg/L, respectively, and the elapsed time was 2,151 days (Table F2). Applying these data to Equation 3 yields a degradation rate of 0.00053 per day. Potentiometric levels shown in Figures F7 and F8 indicate that well TT-26 is located on a direct advective pathway from ABC One-Hour Cleaners. Thus, PCE mass migrates downgradient toward and away from well TT-26. To the extent that migration of PCE mass toward and away from well TT-26 occurred at about equal rates from 1985 to 1991,

the computed degradation rate of 0.00053 per day approximates a long-term average degradation rate. On the other hand, if a significant quantity of the PCE degraded in the vicinity of well TT-26 was replaced by advection, then the degradation rate computed using Equation 3 is probably a minimum rate.

Half-lives of PCE reported in the literature range from about 360 to 720 days (Lucius and others 1990). Applying these half-lives to Equation 3 yields first-order degradation rates ranging between 0.001 and 0.002 per day, about twice to four times the rate computed using concentrations at water-supply well TT-26. An initial first-order degradation rate of 0.00053 per day was applied to the MT3DMS model uniformly to every layer for all stress periods. The final calibrated degradation rate was 0.00050 per day, similarly applied.

Mass-Loading Rate

The concentrations of PCE at monitor wells, at Tarawa Terrace water-supply wells, and at hydrocone locations determined by Roy F. Weston, Inc. (1992, 1994) during Operable Units 1 and 2 (Tables F2–F3, F5–F8) also were used to calculate the mass of PCE still contained in the Tarawa Terrace and Upper Castle Hayne aquifers at the time the Operable Units were in progress (1991–1993). With only three exceptions, the water samples collected by hydrocone were collected at two depths at each location. The collection depth for the majority of the “shallow” samples ranged from about 15 to 25 ft. These data and data from the “S” monitor wells were assigned to an “upper shell.” The collection depth for the majority of the “deep” samples ranged from about 35 to 45 ft. These data and data from the “C” monitor wells and Tarawa Terrace water-supply wells were assigned to a “lower shell.” An altitude also was assigned to each sampling interval. At monitor wells and Tarawa Terrace water-supply wells, altitude was assigned at the mid-point of the open or screened interval. At hydrocone locations, altitude was assigned at the reported sample depth. Using gridding and interpolation techniques, contour maps of PCE concentration and altitude were constructed for the upper and lower shells. The individual shell maps of PCE concentration closely resembled the map shown in Figure F10. The contour maps of altitude of the upper and lower shells were used to compute the volume of aquifer materials between shells. This volume equaled about 186×10^6 cubic feet (ft^3) or about 5.3×10^9 liters. The total volume of aquifer materials was multiplied by an effective porosity of 20 percent to estimate the volume of connected interstices between shells, which equaled about 1.1×10^9 liters (Table F11). The shell contour maps of PCE concentration were first used to determine contours of PCE concentration representing an average condition between the upper and lower shells, termed herein the *average PCE shell*. Contours representing the average PCE shell were constructed at concentration intervals of $2,000 \mu\text{g/L}$ of PCE. The area between each concentration contour was determined using Geographic Information System (GIS) techniques and is termed herein a *subarea*. A total of nine subareas were identified and a representative PCE concentration was

assigned to each subarea, representing the average concentration of the two contours that bounded the subarea. The product of each subarea and its representative concentration was then determined. These products were summed, and the total divided by the total area of PCE contamination represented by the average PCE shell, or about 42 acres. The result of this computation is an area-weighted average PCE concentration for the entire volume of aquifer material between the upper and lower shells, which equaled about 1.4×10^{-3} grams per liter (g/L). The product of this weighted average concentration and the estimated volume of connected interstices between the shells (1.1×10^9 liters) equals the mass of PCE within the volume of aquifer materials between the upper and lower shells, or about 1.5×10^6 grams. This mass in grams was converted to a weight of 3.2×10^3 pounds, or 1.6 tons. The unit weight of PCE is about 1.6 times that of water, or about 101 lbs/ft^3 . Accordingly, the estimated volume of PCE within the aquifer materials between the upper and lower shells at Tarawa Terrace and vicinity equals about 32 ft^3 , or about 240 gallons (gal).

Shell computations similar to those previously described were applied in conjunction with PCE concentration-depth data listed in Table F4 to estimate the PCE mass occurring within the unsaturated zone at and in the vicinity of ABC One-Hour Cleaners from 1987 to 1993. Three data “shells” were created representing PCE concentrations at depths ranging from 1 to 4 ft, from 4 to 9 ft, and from 9 to 14 ft. The soil mass contained within each shell was computed as the product of the estimated volume of each shell and the unit weight of silty sand, estimated to be 170 lbs/ft^3 . Subareas for the uppermost shell were computed based on PCE concentration contours plotted at intervals of 50,000 $\mu\text{g/kg}$. Subareas for the middle and bottom shells were computed using concentration contours plotted at intervals of 20,000 $\mu\text{g/kg}$. The computed area-weighted PCE concentration within each shell was 156,900 $\mu\text{g/kg}$, 88,400 $\mu\text{g/kg}$, and 78,100 $\mu\text{g/kg}$, respectively. Total computed sediment volume of each shell was 29,640 ft^3 , 52,860 ft^3 , and 70,560 ft^3 , respectively. Total PCE mass occurring within the unsaturated zone in the vicinity of ABC One-Hour Cleaners was thus estimated to be about 2,500 lbs, or about 190 gal. This mass and the PCE mass computed previously in solution in groundwater represent a minimum loss of PCE to the subsurface of about 430 gal at ABC One-Hour Cleaners during the period 1953–1985, or an average loss of about 13 gal per year or 230 g/d . This contribution rate must necessarily be considered a minimum because (1) the quantity of PCE removed from the aquifers at Tarawa Terrace water-supply wells from 1953 to 1985 is unknown; (2) the mass of PCE degraded to TCE from 1953 to 1993 was probably large and was not accounted for by the computation of PCE mass; and (3) similarly, the mass of PCE sorbed onto the porous media from 1953 to 1993 also was probably substantial and was not accounted for by the computation of PCE mass. Water-quality data applied to the computation of PCE mass refer only to PCE mass in solution in groundwater. Pankow and Cherry (1996) indicated that computations of contaminant mass similar to those described in the preceding sections possibly represent only a small part

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Table F11. Computation of tetrachloroethylene (PCE) mass in the Upper Castle Hayne aquifer, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, 1991–1993.[µg/L, microgram per liter; ft², square foot]

PCE contour range, in µg/L	Cumulative area, in ft ²	Subarea, in ft ²	Subarea PCE concentration, in µg/L	Subarea-weighted PCE concentration, in µg/L × ft ²
12,000+	2,536.4	2,536.4	12,000	30,436,342
10,000 to 12,000	8,327.7	5,791.3	11,000	63,704,515.1
8,000 to 10,000	19,214.3	10,886.6	9,000	97,979,539.6
6,000 to 8,000	46,394.4	27,180.1	7,000	190,260,492.8
4,000 to 6,000	103,822.4	57,428	5,000	287,139,951.1
2,000 to 4,000	238,065.4	134,243	3,000	402,730,048.4
0 to 2,000	1,793,827.4	1,555,762.1	1,000	1,555,762,094
2.2	1,812,259.5	18,432	2.2	40,660.3
3.4	1,834,571.1	22,311.6	3.4	75,859.4
Total area	1,834,571.0			
Total subarea		1,834,571.0		
Total area-weighted PCE concentration				2,628,129,503

Area-weighted PCE concentration = 1,433 µg/L = 0.0014 gram per liter (sum of PCE subarea-weighted concentrations/total area)

Aquifer volume between shells = 186,072,994 cubic feet

Aquifer volume between shells × effective porosity (20 percent) = 37,214,599 cubic feet

Volume of connected interstices, in liters = 1,053,173,152 (1 cubic foot = 28.3 liters)

PCE mass, in grams = 1,474,442 (product of area-weighted PCE concentration and volume of connected interstices)

PCE weight, in pounds = 3,244 (1 gram = 0.0022 pound)

PCE volume, in cubic feet = 32 (unit weight of PCE = 101 pounds/cubic foot)

PCE volume, in gallons = 240 (1 cubic foot = 7.5 gallons)

of the total contaminant mass in the subsurface. Note that the computations of PCE mass within the Upper Castle Hayne aquifer and the unsaturated zone in the immediate vicinity of ABC One-Hour Cleaners are necessarily highly interpretive and somewhat subjective because of poor data density and some uncertainty regarding water-quality analytical methods and results. Nevertheless, the computed loading rate of about 230 g/d was used as a minimum mass-loading rate and assigned as an initial condition to begin model calibration.

The MT3DMS code requires that a contaminant mass be loaded directly to the water table. Mass loading was assigned to the MT3DMS model in layer 1 at cell 47, 170 and was applied continuously during stress periods 25–408. The location of the septic tank–soil absorption system and related drain field was not specifically determined during ABC One-Hour Cleaners

(Roy F. Weston, Inc. 1994); however, legal depositions indicate the drain field probably was located to the rear and slightly northeast of the ABC One-Hour Cleaners building (Hopf & Higley, P.A., Deposition of Victor John Melts, written communication, April 12, 2001, p. 62–63). Accordingly, cell 47, 170 was located within the active model domain slightly east and behind the building that houses ABC One-Hour Cleaners in order to approximate the probable location of the septic system drain field used by the cleaners. The initial mass loading rate applied to the model was 230 g/d and was adjusted upward during model calibration. The final calibrated mass-loading rate was 1,200 g/d. Distributed arrays of initial PCE concentrations were populated with zero values at all cells for all layers. Thus, the PCE concentration at cell 47, 170 in layer 1 immediately prior to the beginning of mass loading was 0.0 g/ft³.

The primary loss of PCE from operations at ABC One-Hour Cleaners probably was through volatilization. Loss of PCE to the subsurface during operations was probably substantially less than losses to volatilization. Legal depositions (Hopf & Higley, P.A., Deposition of Victor John Melts, written communication, April 12, 2001) indicate that ABC One-Hour Cleaners replenished its PCE supply at a rate of two or three 55-gal drums per month. The unit weight of PCE is about 100 lbs/ft³. Using two drums per month, or 110 gal of PCE, ABC One-Hour Cleaners replaced about 1,470 pounds or about 670,000 grams of PCE monthly. The calibrated mass-loading rate (1,200 g/d) applied to the model represents about 36,000 grams of PCE per month, or about 5 percent of total usage. Using three drums per month, this percentage drops to 3.6 percent. These percentages represent loss not only to wastewater but to filter and still residues that were disposed to the land surface in the immediate vicinity of the cleaners as well as spills from a 250-gal PCE storage tank external and adjacent to the cleaners' building. Because PCE is a high-expense item, efficient use of PCE is critical to a profitable dry-cleaning operation. Thus, the calibrated mass-loading rate indirectly reflects a reasonable operational efficiency and PCE loss rate at ABC One-Hour Cleaners.

PCE lost to the subsurface through operations migrated vertically through the unsaturated zone to the water table. Soil-boring data in the vicinity of ABC One-Hour Cleaners (Figure F5) indicate that PCE occurred vertically through much or all of the unsaturated zone. Aerobic biodegradation of PCE to TCE also occurred within the unsaturated zone at these boring sites (Roy F. Weston, Inc. 1994, Table 5-2). Thus, the actual PCE loss rate to the subsurface from operations at ABC One-Hour Cleaners was possibly somewhat greater than indicated by the calibrated mass-loading rate of 1,200 g/d to the water table.

Model Calibration

Calibration of the Tarawa Terrace fate and transport model was accomplished in a hierarchical process consisting of four successive stages or levels. Simulation results achieved for each calibration level were compared to simulation results of previous levels until results at all levels satisfactorily conformed to appropriate conceptual models and calibration standards. Hydraulic characteristic arrays and model boundary conditions were equivalent at all calibration levels following the final calibration at level 4. In hierarchical order, calibration levels consisted of (1) simulation of predevelopment (steady-state) groundwater-flow conditions, (2) simulation of transient or pumping groundwater-flow conditions, (3) simulation of the fate and transport of a PCE source at ABC One-Hour Cleaners, and (4) computation of concentrations of PCE at the Tarawa Terrace WTP and within the Tarawa Terrace water-distribution network. Calibration levels 1 and 2 are described in detail in Faye and Valenzuela (2007). Calibration levels 3 and 4 are described in this report. Numerical computations performed by MT3DMS for this study used the upstream finite-difference method.

Level 3 Calibration

Hydraulic characteristic and recharge arrays of the MODFLOW flow model assigned following the level 2 calibration were not adjusted during level 3 calibration. Initial values of several transport parameters were modified during trial-and-error calibration and were previously described herein. Final calibrated parameter values are listed in Table F12. Level 3 model calibration was achieved by comparing simulated PCE concentrations at Tarawa Terrace water-supply wells to corresponding observed concentrations. Simulated PCE concentrations were computed at the end of each stress period and were considered representative of an average concentration for the respective month. Field data (observed PCE concentrations) were compared to the simulated concentration closest in time (days) to the simulated day.

Observed PCE concentrations at monitor wells and hydrocone locations were not used for model calibration because of substantial scale differences between the volume of aquifer sampled at monitor wells and the corresponding volume represented by a single cell of the fate and transport model. The volume of sediments represented by a typical model cell located in layer 1 is about 100,000 ft³ and corresponds to a volume of connected interstices of about 20,000 ft³. In contrast, the volume of aquifer sediments sampled by hydrocone was little more than several cubic inches. The volume sampled at a typical monitor well was probably several dozen or perhaps several hundred cubic feet, at most. In addition, PCE mass simulated at a model cell is distributed uniformly and instantaneously throughout the available interstitial volume of the cell at the end of every stress period. Thus, the simulated PCE concentration at the end of every stress period is equal throughout the volume of sediments represented by the model cell. Compare this condition to the highly variable distribution of PCE with depth at hydrocone penetration sites listed in Table F7. Similar or comparable variations in PCE concentration likely occurred across the screened interval of the "S" monitor wells (Table F6). Although mixing occurred during the sampling process, highly variable PCE concentrations determined in monitor wells at various times possibly reflect similar but unobserved variability with depth caused by local heterogeneity and relate to only a tiny percentage of the volume of a model cell. Only by the most unique and rarest of coincidences could one expect highly variable PCE concentrations within an aquifer volume of several dozen or several hundred cubic feet to equal or be comparable to a corresponding simulated concentration uniformly distributed throughout an aquifer volume of 20,000 ft³ in the same area. On the other hand, samples obtained from operating supply wells are composite samples obtained from a large volume of the contributing aquifer or aquifers and reflect well-mixed or average conditions within the water-bearing units. Thus, samples collected at supply wells conform to a considerable degree to the assumptions and limitations that apply to simulated results from the Tarawa Terrace fate and transport model.

Simulation of Tetrachloroethylene (PCE) Migration**Table F12.** Calibrated model parameter values used for simulating groundwater flow and contaminant fate and transport, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.[ft/d, foot per day; ft³/d, cubic foot per day; ft³/g, cubic foot per gram; g/ft³, gram per cubic foot; d⁻¹, 1/day; g/d, gram per day; ft, foot; ft²/d, square foot per day; —, not applicable]

Model parameter	Model layer number ²						
	1	2	3	4	5	6	7
Predevelopment groundwater-flow model (conditions prior to 1951)							
Horizontal hydraulic conductivity, K_h (ft/d)	12.2–53.4	1.0	4.3–20.0	1.0	6.4–9.0	1.0	5.0
Ratio of vertical to horizontal hydraulic conductivity, K_v/K_h ³	1:7.3	1:10	1:8.3	1:10	1:10	1:10	1:10
Infiltration (recharge), I_R (inches per year)	13.2	—	—	—	—	—	—
Transient groundwater-flow model, January 1951–December 1994							
Specific yield, S_y	0.05	—	—	—	—	—	—
Storage coefficient, S	—	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}	4.0×10^{-4}
Infiltration (recharge), I_R (inches per year)	6.6–19.3	—	—	—	—	—	—
Pumpage, Q_k (ft ³ /d)	See footnote ⁴	—	See footnote ⁴	—	0	—	0
Fate and transport of tetrachloroethylene (PCE) model, January 1951–December 1994							
Distribution coefficient, K_d (ft ³ /g)	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}	5.0×10^{-6}
Bulk density, ρ_b (g/ft ³)	77,112	77,112	77,112	77,112	77,112	77,112	77,112
Effective porosity, n_E	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Reaction rate, r (d ⁻¹)	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}	5.0×10^{-4}
Mass-loading rate ⁵ , $q_s C_s$ (g/d)	1,200	—	—	—	—	—	—
Longitudinal dispersivity, α_L (ft)	25	25	25	25	25	25	25
Transverse dispersivity, α_T (ft)	2.5	2.5	2.5	2.5	2.5	2.5	2.5
Vertical dispersivity, α_V (ft)	0.25	0.25	0.25	0.25	0.25	0.25	0.25
Molecular diffusion coefficient, D^* (ft ² /d)	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}	8.5×10^{-4}

¹ Symbolic notation used to describe model parameters obtained from Chiang and Kinzelbach (2001)² Refer to Chapter B (Faye 2007) and Chapter C (Faye and Valenzuela 2007) reports for geohydrologic framework corresponding to appropriate model layers; aquifers are model layers 1, 3, 5, and 7; confining units are model layers 2, 4, and 6³ For model cells simulating water-supply wells, vertical hydraulic conductivity (K_v) equals 100 feet per day to approximate the gravel pack around the well⁴ Pumpage varies by month, year, and model layer; refer to Chapter K report (Maslia et al. In press 2008) for specific pumpage data⁵ Introduction of contaminant mass began January 1953 and terminated December 1984

Simulated and corresponding observed PCE concentrations at Tarawa Terrace and local water-supply wells are listed in Table F13 and are portrayed in this report as a scatter diagram (Figure F12) and as time-series graphs at individual wells (Figures F13–F17). The calibration target range for observed PCE concentrations was $\pm 1/2$ -order of magnitude of the observed concentration. For concentrations that are reported as not detected (ND), the lower calibration target was selected as 1 $\mu\text{g/L}$; the upper limit selected was the analytical detection limit (Table F2).

Simulated concentrations and observed concentrations reported as not detected do not compare favorably at water-supply well TT-23. Faye and Green (2007) described

an enhanced rate of biodegradation of PCE at well TT-23 possibly caused by the occurrence of BTEX compounds in conjunction with PCE in the groundwater. This local enhancement in the rate of biodegradation at well TT-23, and, possibly at other wells, was not accounted for in MT3DMS simulations and possibly explains at least part of the disparity between observed and simulated PCE concentrations.

All simulated PCE concentrations in local water-supply wells labeled as “RW” compared favorably to calibration target limits. Of the 18 paired data that corresponded to Tarawa Terrace water-supply wells and included an observed value for PCE concentration, 11 comparisons of simulated to observed concentrations failed the $1/2$ -order of magnitude calibration

Simulation of Tetrachloroethylene (PCE) Migration

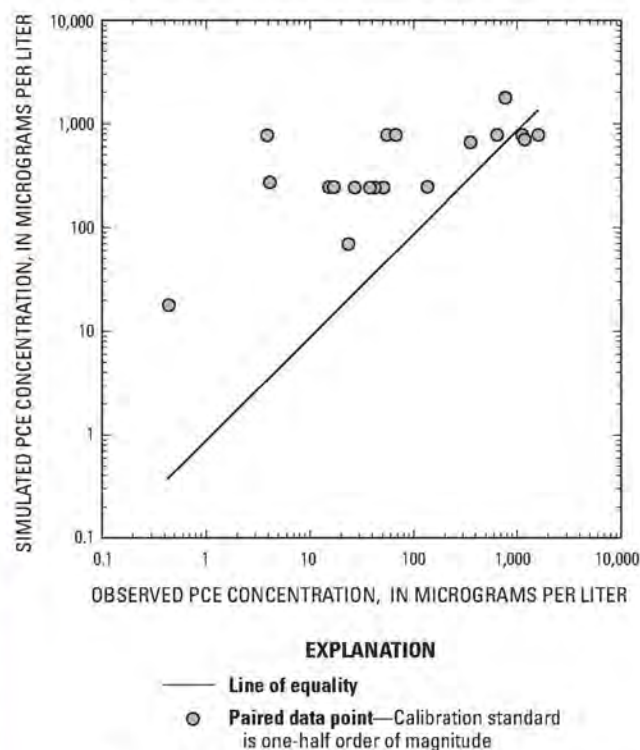
Table F13. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply wells and calibration target range, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[µg/L, microgram per liter; ND, not detected; J, estimated]

Site name	Date	PCE concentration, in µg/L		Calibrated target range, in µg/L
		Observed	Simulated	
¹ RW1	7/12/1991	ND	0.0	0.0–2.0
¹ RW2	7/12/1991	760	1,804	240–2,403
¹ RW3	7/12/1991	ND	0.0	0.0–2.0
² TT-23	1/16/1985	132	254	41.7–417
	2/12/1985	37.0	254	11.7–117
	2/19/1985	26.2	253	8.3–82.8
	2/19/1985	ND	253	0.0–10.0
	3/11/1985	14.9	253	4.7–47.1
	3/11/1985	16.0	253	5.2–52.5
	3/12/1985	40.6	253	12.8–128
	3/12/1985	48.0	253	15.4–154
	4/9/1985	ND	265	0.0–2.0
	9/25/1985	4.0	279	0.3–12.6
	7/11/1991	ND	193	0.0–5.0
² TT-25	2/5/1985	ND	6.2	0.0–10.0
	4/9/1985	ND	8.6	0.0–2.0
	9/25/1985	0.43J	18.1	0.14–1.4
	10/29/1985	ND	20.4	0.0–10.0
	11/4/1985	ND	20.4	0.0–10.0
	11/13/1985	ND	20.4	0.0–10.0
	12/3/1985	ND	22.8	0.0–10.0
	7/11/1991	23.0	72.6	7.3–72.7
² TT-26	1/16/1985	1,580	804	500–5,000
	2/12/1985	3.8	804	1.2–12
	2/19/1985	55.2	798	17.5–175
	2/19/1985	64.0	798	20.2–202
	4/9/1985	630	801	199–1,999
	6/24/1985	1,160	732	367–3,668
	9/25/1985	1,100	788	348–3,478
	7/11/1991	340	670	111–1,107
² TT-30	2/6/1985	ND	0.0	0.0–10.0
² TT-31	2/6/1985	ND	0.15	0.0–10.0
² TT-52	2/6/1985	ND	0.0	0.0–10.0
² TT-54	2/6/1985	ND	5.8	0.0–10.0
	7/11/1991	ND	30.4	0.0–5.0
² TT-67	2/6/1985	ND	3.9	0.0–10.0

¹See Figure F6 for location²See Figure F1 for location

Note: Calibration target ranges for analyses listed as not detected are detection limits noted in Table F2

**Figure F12.** Simulated and observed tetrachloroethylene (PCE) concentrations at selected water-supply wells, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1985–July 1991.

standard (Table F13). Of the total of 36 comparisons of simulated to observed PCE concentrations in all water-supply wells used to calibrate the Tarawa Terrace fate and transport model (Table F13), including “not detected” results, 17 comparisons or 47 percent conformed to the calibration standard, and 19 comparisons or 53 percent violated the standard. A scatter diagram of simulated and observed PCE concentrations is shown in Figure F12 and indicates that simulated PCE concentrations mainly exceeded corresponding observed concentrations. A geometric bias that compares simulated and observed concentrations also was computed. An inclusive bias was computed using all 19 paired data at water-supply wells and equaled 5.9. A selected bias also was computed that excluded paired data at water-supply well TT-23 and equaled 3.9 (Maslia et al. 2007). Both results indicate that simulated PCE concentrations moderately to substantially overpredicted observed concentrations at water-supply wells.

Time-series graphs of simulated PCE concentrations in water-supply wells RW2, TT-23, TT-25, TT-26, and TT-54 indicate that PCE concentrations in these wells equaled or exceeded the current maximum contaminant level (MCL) for PCE of 5 µg/L (USEPA 2003) during the service periods of the wells (Faye and Valenzuela 2007) (Figures F13–F17). Well RW2 was located in a commercial building (furniture store) adjacent to ABC One-Hour Cleaners on SR 24. Simulated PCE concentrations at this site probably resemble

Simulation of Tetrachloroethylene (PCE) Migration

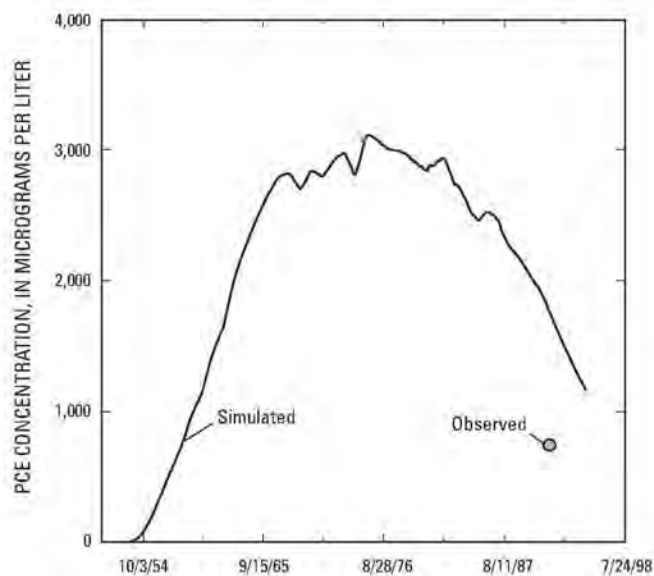


Figure F13. Simulated and observed tetrachloroethylene (PCE) concentrations at local water-supply well RW2, near ABC One-Hour Cleaners, Jacksonville, North Carolina, January 1951–December 1994 (see Figure F6 for location).

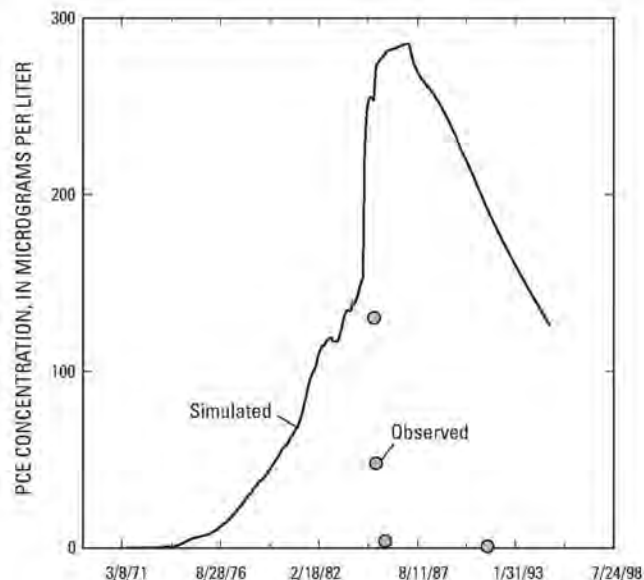


Figure F14. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-23, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1969–December 1994 (see Figure F6 for location).

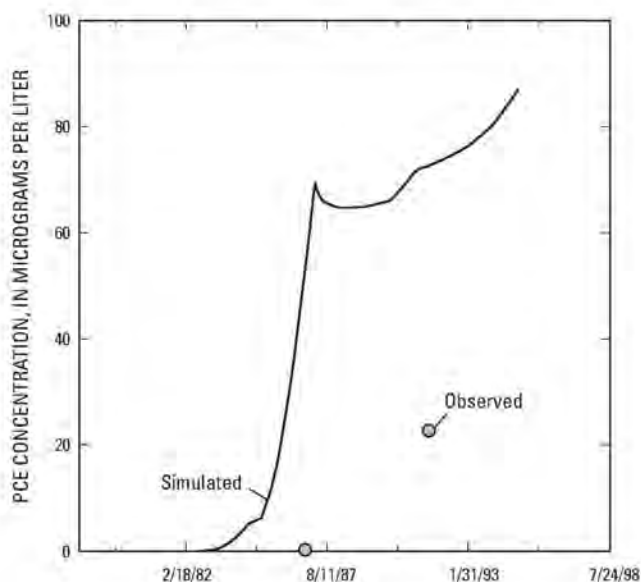


Figure F15. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-25, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1978–December 1994 (see Figure F6 for location).

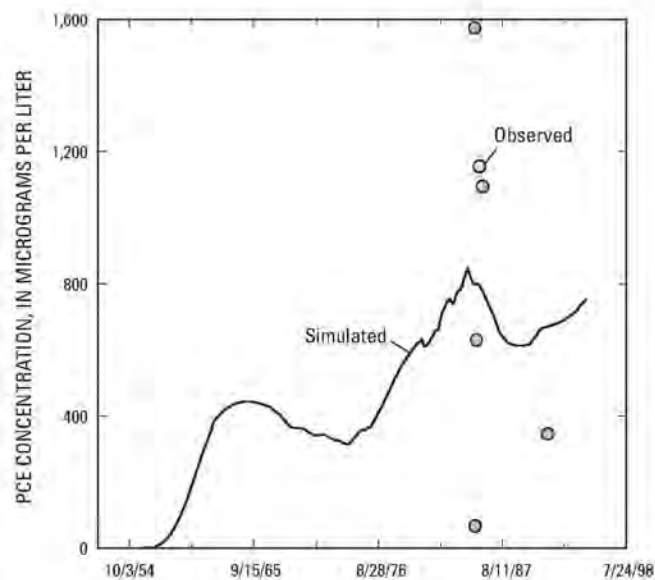


Figure F16. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-26, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1952–December 1994 (see Figure F6 for location).

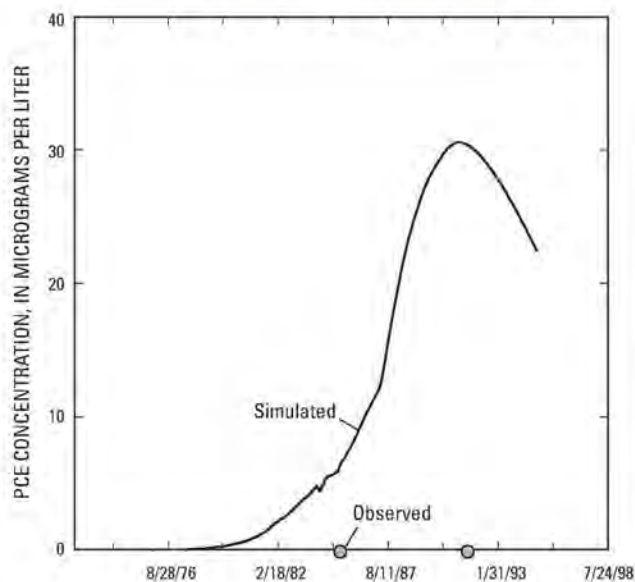


Figure F17. Simulated and observed tetrachloroethylene (PCE) concentrations at water-supply well TT-54, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1970–December 1994 (see Figure F6 for location).

groundwater contamination in the immediate vicinity of the cleaners. Pumpage and operation data were not available for well RW2. Regardless, pumpage from well RW2 was considered insignificant for modeling purposes, and simulated pumpage was assigned as 0.0 ft³/d for the entire period of simulation. Simulated PCE concentrations at Tarawa Terrace water-supply wells approximate an historical record of contaminated groundwater delivered to the Tarawa Terrace WTP, as well as the attenuation of PCE concentrations subsequent to the termination of pumping at the wells. Of the water-supply wells contributing PCE to the Tarawa Terrace WTP, well TT-26 was the earliest and by far the dominant contributor (Figure F16). Simulated breakthrough of PCE at a concentration above 5 µg/L occurs at about December 1956 or January 1957. The simulated PCE concentration increases rapidly following breakthrough to 100 µg/L at about April 1959. Simulated PCE concentrations remain greater than 100 µg/L during the remainder of the simulation period and peak at about 850 µg/L during July 1984, several months prior to the termination of operations at well TT-26 during February 1985. At the time well TT-23 was placed in service, at or about August 1984, the simulated PCE concentration of the discharge water is about 150 µg/L and increases gradually to this level following a breakthrough of 5 µg/L at about December 1974 at the well site (Figure F14). Following the onset of pumping at well TT-23, the simulated PCE concentration increases rapidly to about 280 µg/L by April 1985, when the well was probably removed from service. The simulated PCE concentration at well TT-25 increases

to 5 µg/L about June or July 1984 and gradually increases to a maximum concentration of about 87 µg/L at the end of the simulation period during December 1994 (Figure F15). The simulated MCL occurs at well TT-54 (Figure F17) during June 1984. The maximum simulated PCE concentration of about 31 µg/L at well TT-54 occurs during February 1991; however, this condition is not supported by field data (Tables F2 and F13).

Plan views of PCE concentration plumes simulated within model layer 1 (the combined Tarawa Terrace aquifer and Upper Castle Hayne aquifer–River Bend unit) during December 1960, December 1968, December 1975, December 1984, March 1987, and December 1994 are shown in Figures F18–F23. Simulated potentiometric levels also are shown for the respective months and layer. Simulated pumping at original Tarawa Terrace water-supply wells TT-26, TT-27, TT-28, TT-29, and TT-45 begins during January 1952. Operation of well TT-29 was terminated about 1958 (Faye and Valenzuela 2007). Available construction data for the original Tarawa Terrace wells are incomplete (Table F9) but indicate that each of the wells probably was open to the Upper Castle Hayne aquifer–River Bend unit and the Upper Castle Hayne aquifer–Lower unit, the Lower unit either directly by open interval or indirectly by gravel or sand packing within the annular space of the well bore. Accordingly, simulated pumpage at these wells was assigned entirely to either the Upper Castle Hayne aquifer–River Bend unit or Lower unit. Simulated mass loading of PCE to model layer 1 at cell 47, 170 begins during January 1953. By December 1960, a small continuous PCE plume develops along descending hydraulic gradients between ABC One-Hour Cleaners and well TT-26 (Figure F18). Simulated breakthrough of PCE at well TT-26 at the MCL concentration occurs by January 1957, and the concentration increases to about 265 µg/L by December 1960 (Figure F16). Drawdown caused by pumping at water-supply wells west of ABC One-Hour Cleaners significantly flattened the potentiometric surface and related hydraulic gradients between the cleaners and wells TT-27, TT-28, and TT-29, and no simulated breakthrough of PCE occurs at these wells during their assigned periods of operation (Faye and Valenzuela 2007). The simulated PCE concentration during December 1960 at the mass-loading cell (47, 170) equals about 88,000 µg/L. Simulated PCE concentrations in water delivered to the Tarawa Terrace WTP from well TT-26 during 1960 ranges from about 169 to 265 µg/L. Computed breakthrough of PCE at the Tarawa Terrace WTP at the MCL concentration occurs by November 1957 (Maslia et al. 2007).

The areal extent of the simulated PCE plume within model layer 1 approximately doubles between December 1960 and December 1968 (Figures F18 and F19), and plume migration diverts partially southward toward water-supply wells operating near and within the Tarawa Terrace housing areas (Figure F19). Water-supply wells TT-52, TT-53, and TT-54 began operation during 1962. Pumpage at these wells was assigned either entirely to the Upper Castle Hayne aquifer or was equally divided between the

Simulation of Tetrachloroethylene (PCE) Migration

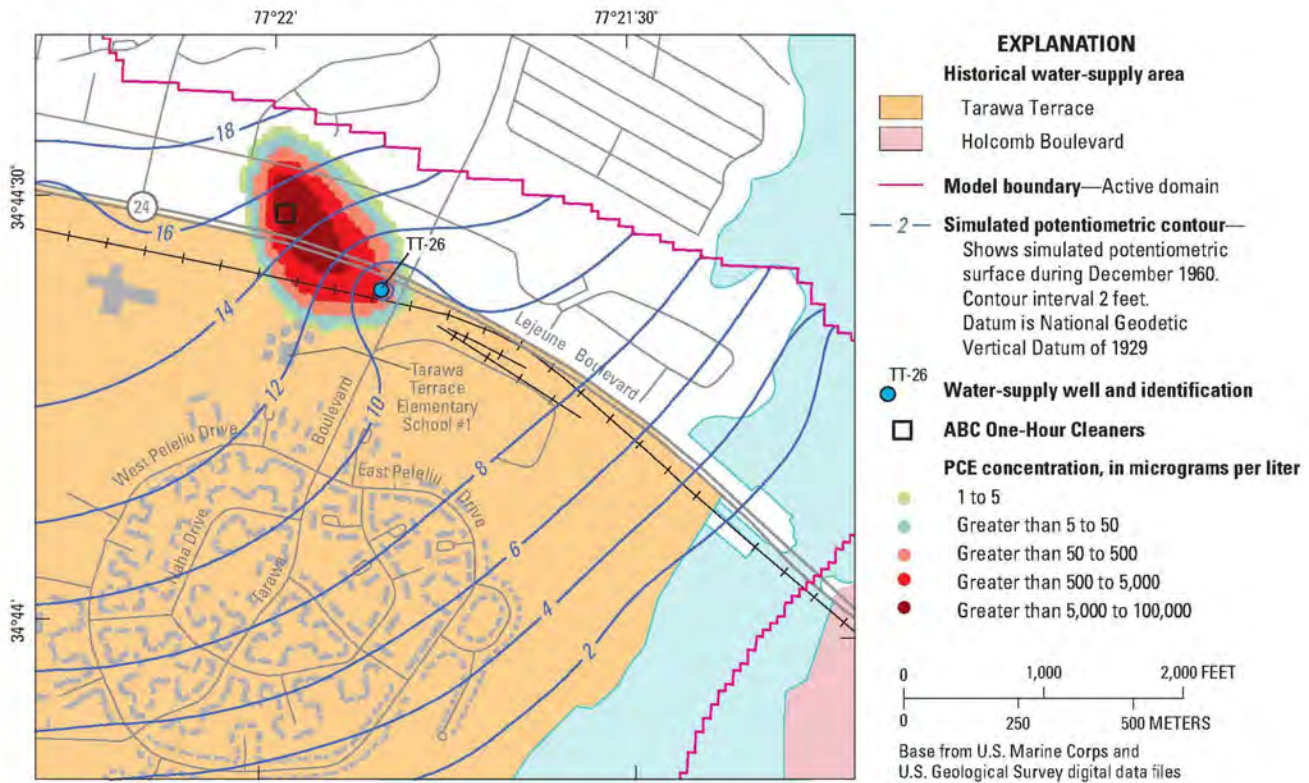


Figure F18. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1960.

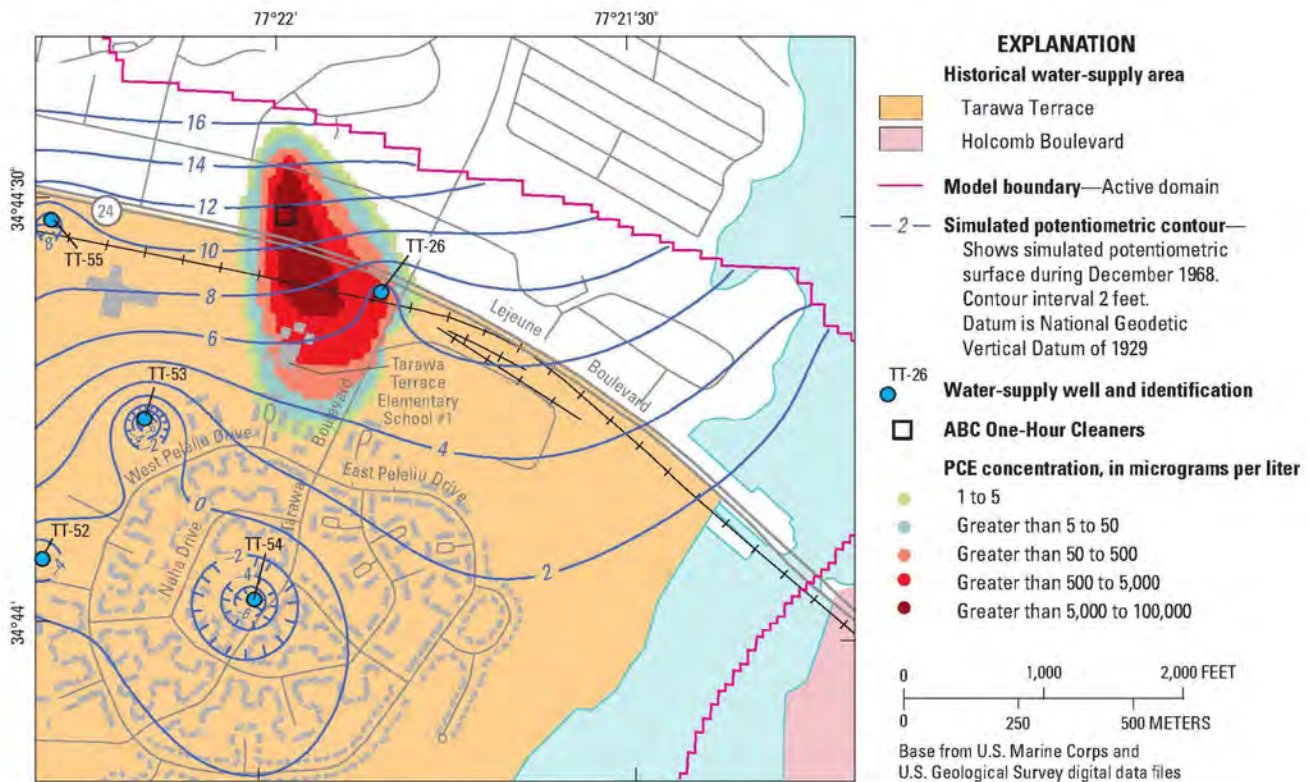


Figure F19. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1968.

Simulation of Tetrachloroethylene (PCE) Migration

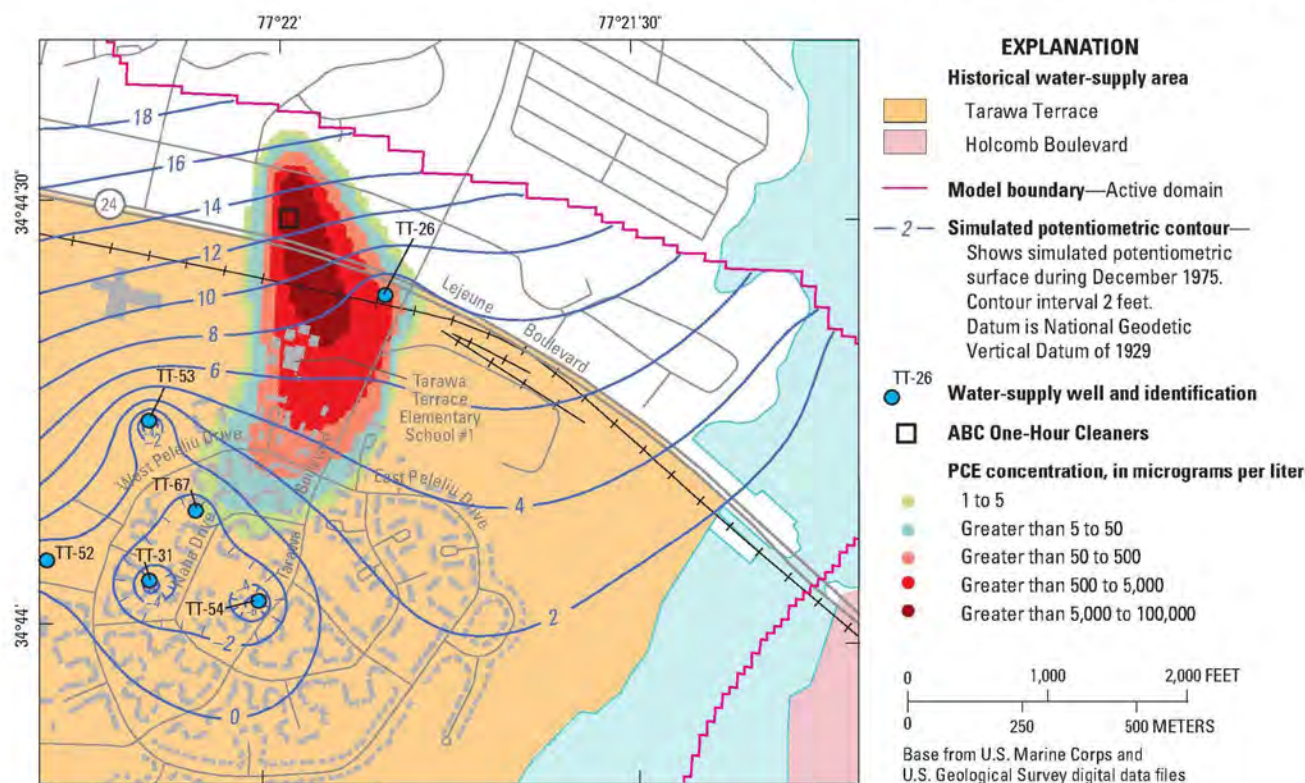


Figure F20. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1975.

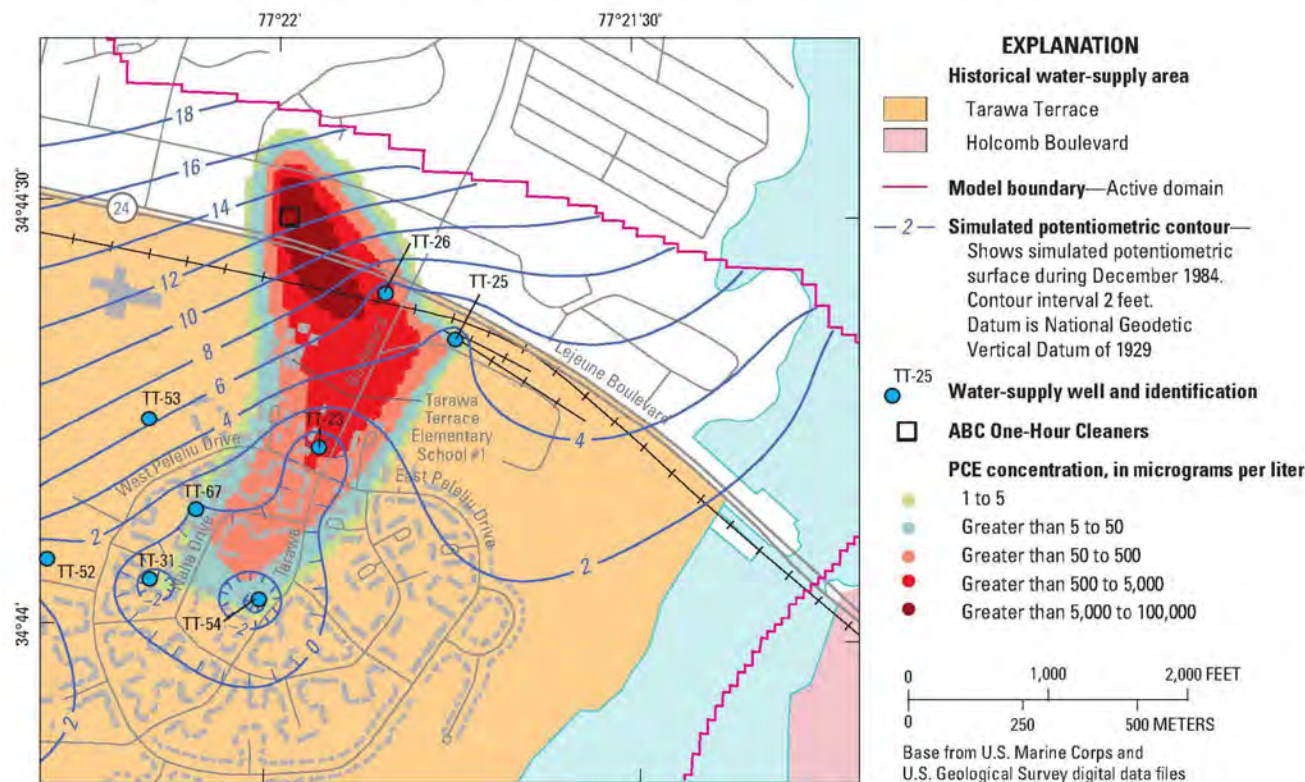


Figure F21. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1984.

Simulation of Tetrachloroethylene (PCE) Migration

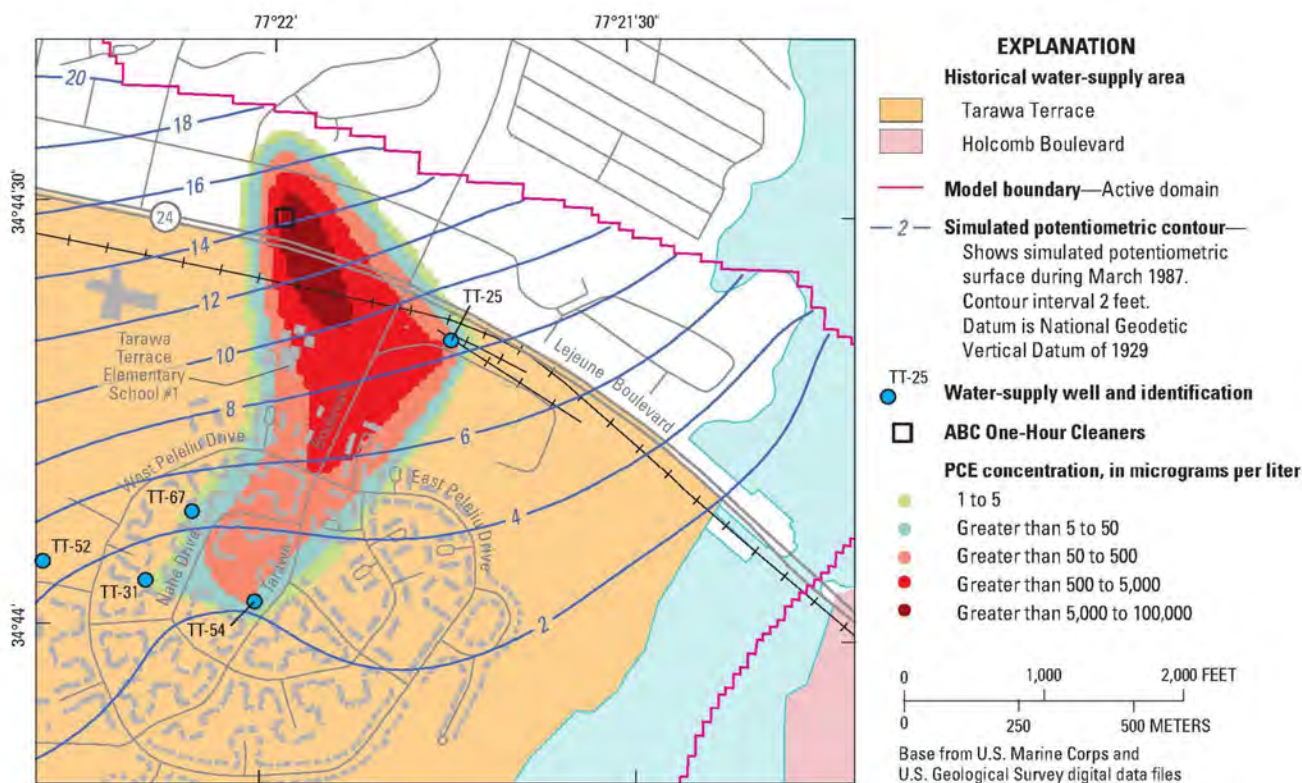


Figure F22. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, March 1987.

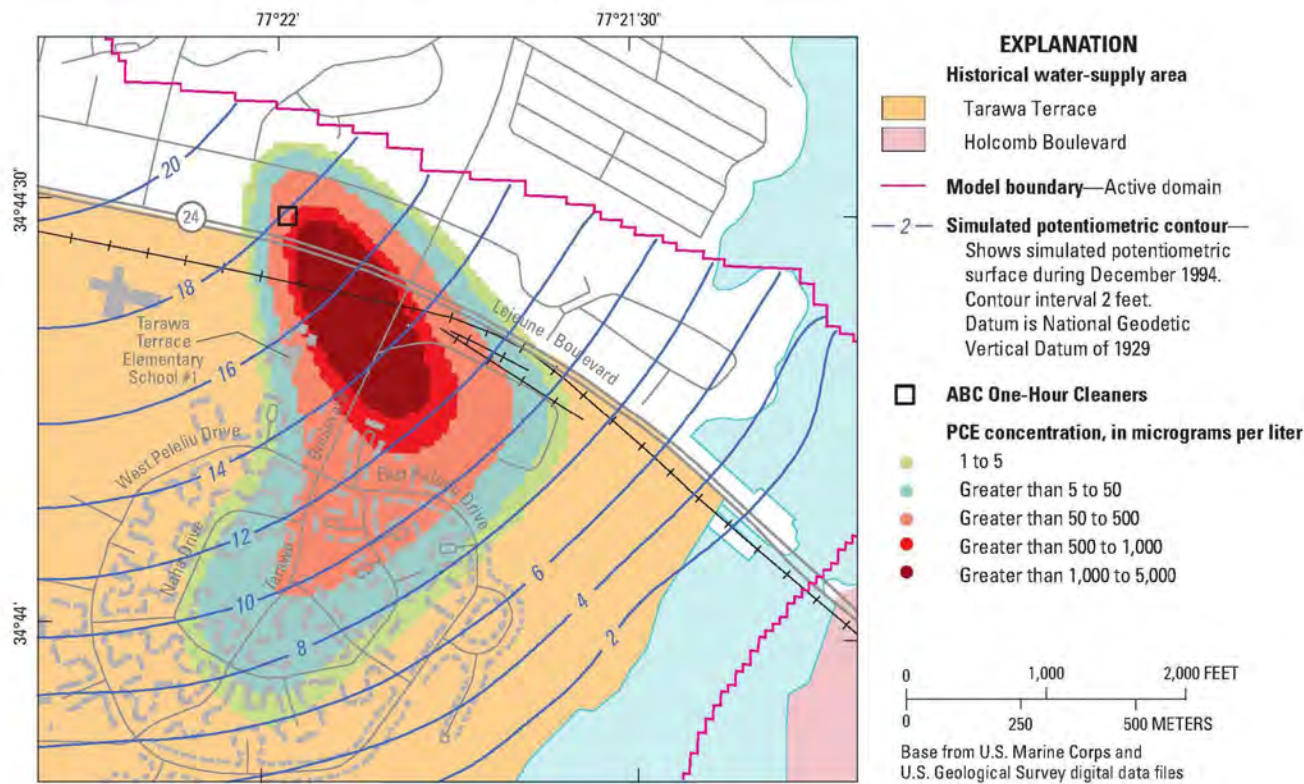


Figure F23. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 1, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1994.

Simulation of Tetrachloroethylene (PCE) Migration

River bend and Lower units of the Upper Castle Hayne aquifer (Faye and Valenzuela 2007), and caused hydraulic gradients in the vicinity of ABC One-Hour Cleaners to shift gradually from generally southeast during December 1960 to generally southward by December 1968 (Figures F18 and F19). This shift in hydraulic gradients also caused PCE mass to be diverted southward away from water-supply well TT-26 and probably caused the downward trend in PCE concentration at this well beginning at about January 1965 (Figure F16). During the same period, the simulated concentration of PCE at the mass-loading site in layer 1 (cell 47, 170) decreases from about 88,000 $\mu\text{g/L}$ to about 86,900 $\mu\text{g/L}$, possibly as a result of dilution from uncontaminated ground-water flowing along hydraulic gradients from the northwestern part of the active model domain (general-head boundary) toward ABC One-Hour Cleaners (Figure F19). Original water-supply wells TT-28 and TT-45 were still in service during December 1968. Original water-supply well TT-27 was removed from service, probably about 1963 and was replaced by water-supply well TT-55 (Faye and Valenzuela 2007). Construction data for well TT-55 are not available, and construction and contributing aquifers were assumed similar to other original Tarawa Terrace water-supply wells. No simulated breakthrough of PCE occurs at wells TT-27 or TT-55 during their assigned periods of operation. Simulated PCE concentrations in water delivered to the Tarawa Terrace WTP from well TT-26 during 1968 ranges from about 367 to 402 $\mu\text{g/L}$.

By December 1975, southward migration and expansion of the PCE plume within model layer 1 had extended to the northern part of the Tarawa Terrace housing area I (Figure F20). Water-supply wells TT-31 and TT-67 began operation, probably during 1972 and 1973 (Faye and Valenzuela 2007), which further increased the southward-trending hydraulic gradients noted during December 1968 (Figures F19 and F20). Water-supply well TT-30, located near water-supply well TT-28 and substantially west of water-supply well TT-26, probably began operation during 1972 following the termination of service at well TT-28 during 1971. No simulated breakthrough of PCE at well TT-30 occurs during its assigned period of operation. With the exception of well TT-26, service at all of the original Tarawa Terrace water-supply wells, including TT-55, was abandoned by December 1975, and water supplied to the Tarawa Terrace WTP was entirely from wells TT-26, TT-30, TT-31, TT-52, TT-53, TT-54, and TT-67. The simulated PCE concentration at the mass-loading site (cell 47, 170) had decreased to about 80,700 $\mu\text{g/L}$ by December 1975. Simulated PCE concentrations in water delivered to the Tarawa Terrace WTP from well TT-26 during 1975 ranges from about 355 to 367 $\mu\text{g/L}$.

The southward migration of the PCE plume within model layer 1 continued after December 1975 and, by December 1984, had terminated near the center of Tarawa Terrace housing area I (Figure F21). An additional water-supply well, TT-23, was placed in service during 1984, and service at water-supply well TT-30 was terminated shortly afterward (Faye and Valenzuela 2007). During 1984, wells

TT-23 and TT-26 delivered water to the Tarawa Terrace WTP at simulated PCE concentrations ranging from about 224 to 255 $\mu\text{g/L}$ and 791 to 805 $\mu\text{g/L}$, respectively. Well TT-23 was constructed with screens open to the Upper and Middle Castle Hayne aquifers, and PCE-contaminated water from the Upper Castle Hayne aquifer was diluted with water from the Middle Castle Hayne aquifer that contained little or no PCE. Water-supply well TT-25 was placed in service probably during 1982 and was located about 500 ft southeast of well TT-26. Pumping at this well in conjunction with the operation of well TT-26 further diverted PCE mass toward well TT-26. The simulated PCE concentrations at well TT-26 continue to increase during most of the period December 1975–December 1984 (Figures F16 and F21). The simulated PCE plume migrates to the vicinity of well TT-25 by December 1984 (Figure F21); however, PCE concentrations in the discharge water were below the MCL concentration at this time (Figure F15). In addition, well TT-25 was constructed as a multiaquifer well, similar to well TT-23, causing dilution of PCE-contaminated water obtained from the Upper Castle Hayne aquifer. During 1984, simulated PCE concentrations in discharge water from well TT-25 ranges from about 2.5 to 6.0 $\mu\text{g/L}$. Simulated breakthrough at the PCE MCL concentration at well TT-25 occurs about June or July 1984. The simulated PCE concentration at the mass-loading cell (47, 170) declines to about 72,200 $\mu\text{g/L}$ by December 1984.

Service at water-supply wells TT-23 and TT-26 was terminated during early 1985 because of PCE contamination. Service at all Tarawa Terrace water-supply wells was terminated by March or April 1987. Concentrations of PCE and potentiometric levels in model layer 1 during March 1987 are shown in Figure F22. The simulated distribution of PCE is similar to that shown for December 1984 (Figure F21), with the exception of additional migration of PCE toward water-supply well TT-31 and a slight shift in migration of the PCE plume center of mass from south to southeast.

Simulated mass loading of PCE to model layer 1 at cell 47, 170 terminates after December 1984. Accordingly, a supply of additional PCE mass to model layer 1 is no longer available beginning January 1985. In addition, (1) substantial quantities of PCE mass are no longer removed from model layers 1 and 3 by wells, following the termination of service at these wells during 1985, and (2) PCE migration is no longer influenced by pumping at wells after March or April 1987. These simulated conditions prevail during most of the period December 1984–December 1994, the end of groundwater-flow and fate and transport simulations (Figure F23). By December 1994, the center of mass of PCE has migrated about 700 ft southeast of ABC One-Hour Cleaners and maximum PCE concentrations at the center of mass have decreased to about 3,300 $\mu\text{g/L}$. Conversely, simulated PCE concentrations in the vicinity of water-supply wells TT-25 and TT-54 have increased to about 87 $\mu\text{g/L}$ and 22 $\mu\text{g/L}$, respectively, by December 1994. Increases in simulated PCE concentration at both wells occur mostly as a result of PCE migration along natural groundwater-flow gradients between December 1984 and December 1994.

Simulation of Tetrachloroethylene (PCE) Migration

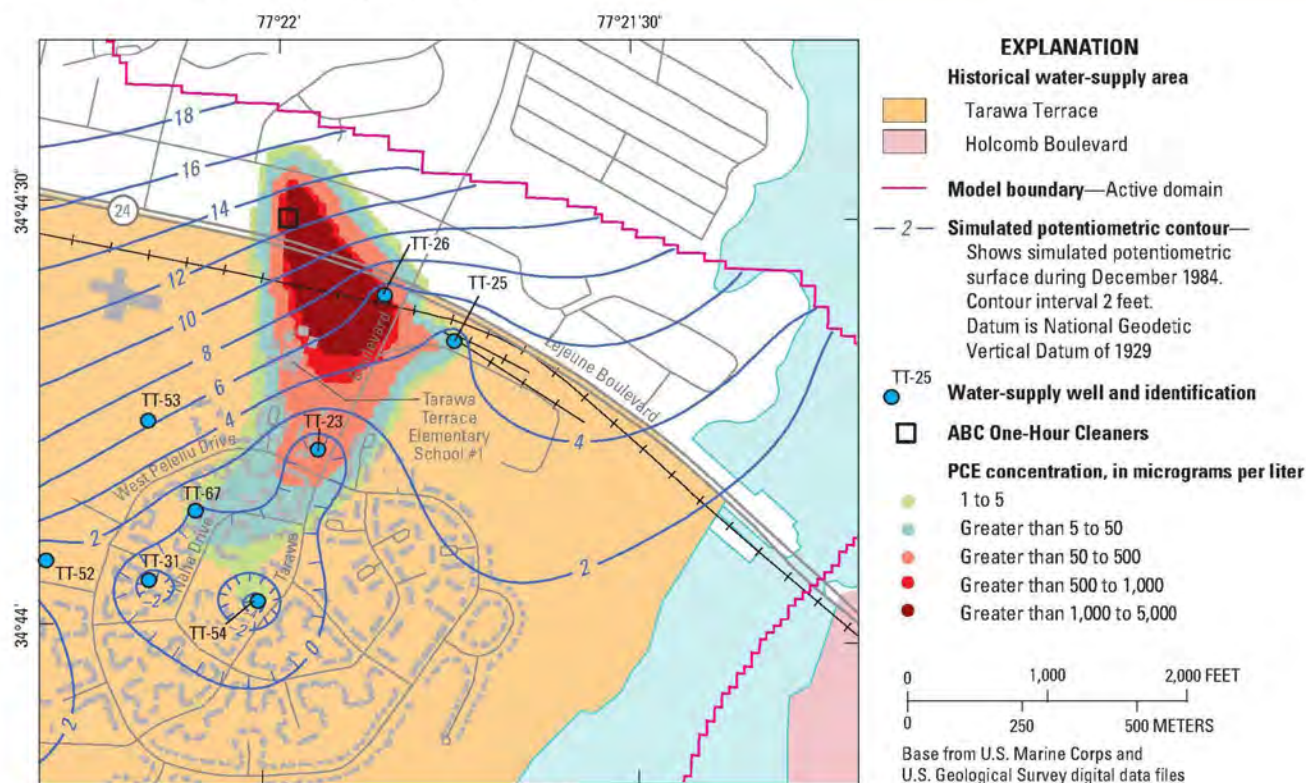


Figure F24. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 3, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1984.

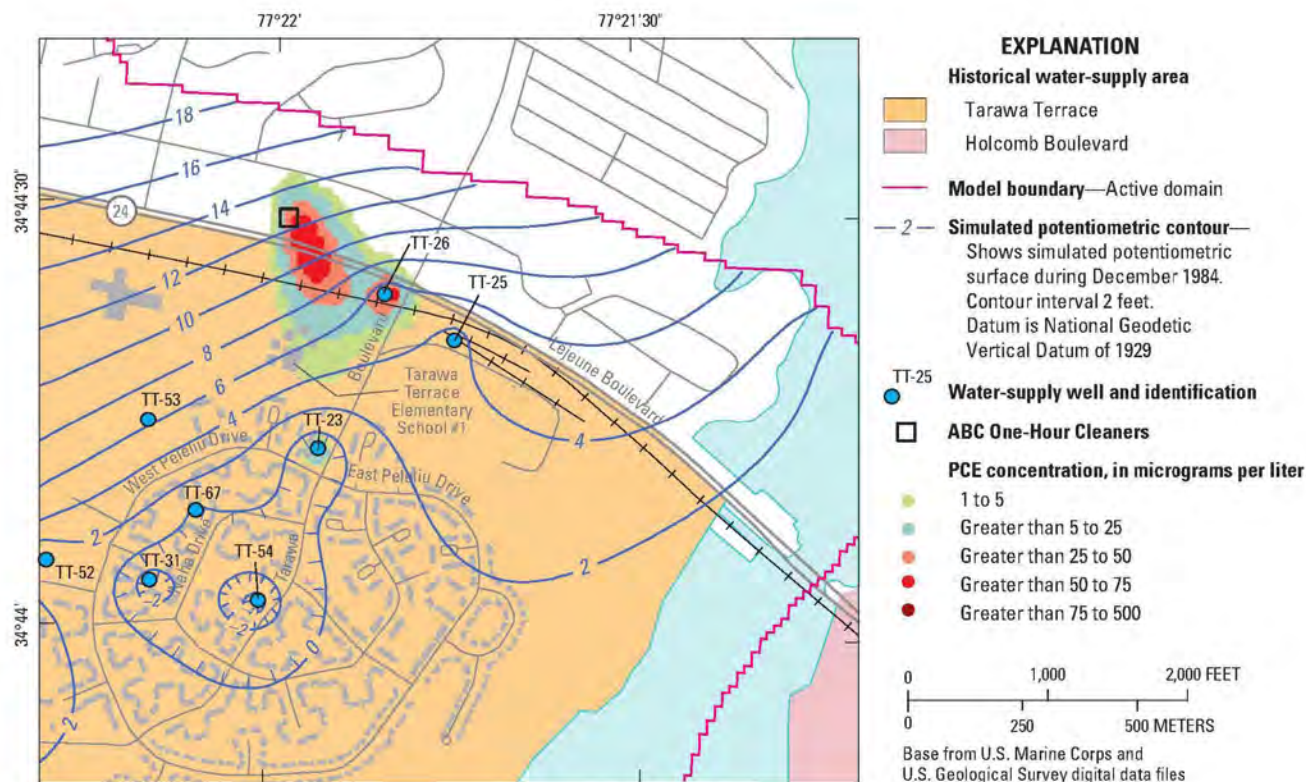


Figure F25. Simulated distribution of tetrachloroethylene (PCE) and potentiometric levels within part of model layer 5, Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, December 1984.

Simulation of Tetrachloroethylene (PCE) Migration

Downward vertical migration of PCE to model layers 3 and 5 also was simulated. By December 1984, the distribution of PCE within layer 3 (Figure F24) closely resembles the corresponding distribution within layer 1 (Figure F21), albeit with substantially lower concentrations. The maximum PCE concentration of about 3,600 $\mu\text{g/L}$ occurs slightly east and south of the mass-loading cell. Simulated migration of PCE occurs to the south and southeast largely along hydraulic gradients caused by pumping from model layers 1 and 3 and to the north and northwest along concentration gradients. Potentiometric gradients within model layer 5 are similar to those in layers 3 and 1; however, concentrations of PCE are substantially lower (Figure F25). The occurrence of PCE is limited largely to the area between ABC One-Hour Cleaners and water-supply well TT-26, with minor occurrences southward toward water-supply well TT-23. Simulated contamination within model layer 5 also occurs in the immediate vicinity of water-supply well TT-23, indicating possible "capture" of contaminated water from the well bore caused by pumping at this well and water-supply wells TT-31, TT-54, and TT-67, and the subsequent lowering of heads in model layers 3 and 5. The maximum simulated concentration of PCE in model layer 5 is about 140 $\mu\text{g/L}$ and occurs slightly east of the mass-loading cell—cell 47, 170.

Results of mass balance simulations by the calibrated model are summarized in Figure F26. Of the total PCE mass removed from all model layers during the period of fate and transport simulation (January 1953–December 1994), wells are shown to have removed the least mass (2.4×10^6 grams) and biodegradation the most (9.2×10^6 grams). The simulated sorption process removed about 5.8×10^6 grams of PCE. Residual PCE mass still present in the model aquifers and confining units during December 1994 totals about 2.8×10^6 grams. Total PCE mass loaded to the model from January 1953 to December 1984 equals about 14.0×10^6 grams. Mass sorbed also is biodegraded. Thus, total mass removed from the model is the sum of total mass removed by wells and by biodegradation. The algebraic difference between mass loaded to, remaining in, and removed from the model of 4.0×10^5 grams is the result of rounding error and simulation discrepancy.

Mass balance calculations also can be used to determine the quantity of PCE mass in solution in all model layers at the end of any stress period. Most of the data used to compute the quantity of PCE mass in solution (Table F11) were collected during December 1991 and April 1992 (Tables F7 and F5). These months are represented in the model by stress periods 492 and 496, respectively. Algebraic manipulation of mass

balance data computed for stress period 494, representing February 1992, indicate the simulated PCE mass in solution at that time equals about 1.0×10^6 grams. The computed PCE mass in solution (Table F11) equals 1.5×10^6 grams and represents, for the most part, PCE quantities in the most contaminated parts of the Upper Castle Hayne aquifer—River Bend and Lower units (model layers 1 and 3). Model simulations indicate that the vast majority of PCE mass occurring in the model during stress period 494 also resided in layers 1 and 3. Although the PCE mass calculation is interpretive and somewhat subjective, the reasonably close agreement between simulated and computed mass in solution within the active model domain at the same time further corroborates the calibration of the fate and transport model.

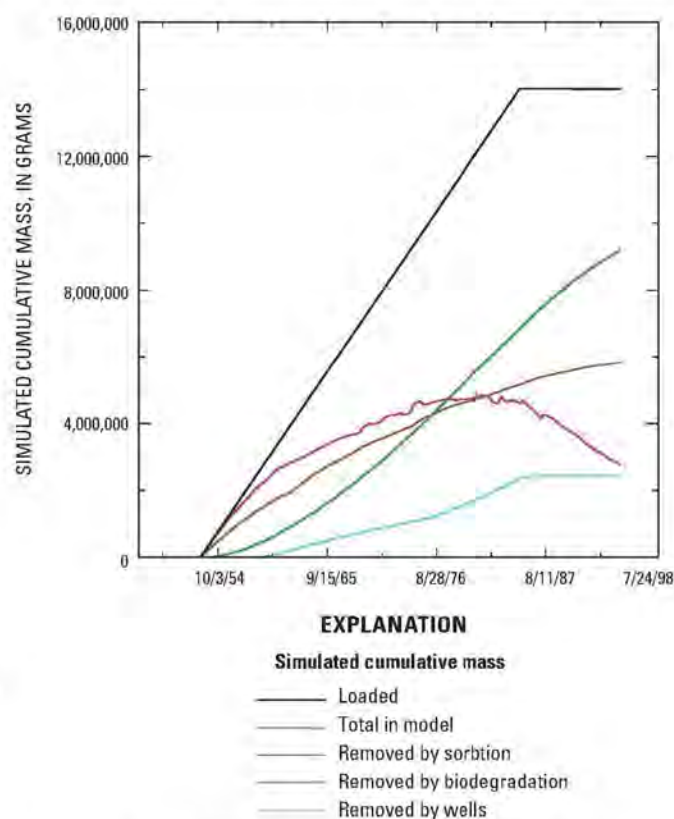


Figure F26. Simulated cumulative mass balance of tetrachloroethylene (PCE), Tarawa Terrace and vicinity, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1953–December 1994.

Simulation of Tetrachloroethylene (PCE) Migration

Level 4 Calibration

The final stage of model calibration employed a simple mixing (flow-weighted average) model to compute PCE concentrations delivered to the Tarawa Terrace WTP from all active water-supply wells and subsequently to the Tarawa Terrace water-supply network. For each stress period (month) of the simulation period (from January 1951 to December 1994), the PCE concentration simulated at each active water-supply well is weighted by the respective well discharge to compute a weighted-average PCE concentration. This weighted-average concentration was considered the monthly average PCE concentration delivered to the Tarawa Terrace WTP. The results of these computations compared to an analysis of a water sample collected at a point in time, either at the Tarawa Terrace WTP or at a location within the Tarawa Terrace water-supply network, such as an outdoor or indoor faucet, are summarized in Table F14. The computed PCE concentration is compared to the observed PCE concentration on a same-month basis; that is, if a sample date was reported as May 1, 1982, then the corresponding computed PCE concentration was the weighted-average concentration for the month of May 1982. The calibration standard applied to the comparisons of computed and observed PCE concentrations was $\pm 1/2$ -order of magnitude of the observed value. Many observed analyses were reported as “not detected,” and corresponding detection limits were assigned as the calibration standard, similar to the standard applied to water-supply well concentration data. Detection limits pertinent to the 1982 analyses are unknown but probably were not greater than 10 $\mu\text{g/L}$. Detection limits for the analyses of February 19, 1985, and March 11–12, 1985, were 2 $\mu\text{g/L}$. Detection limits for all other analyses listed in Table F14 were 10 $\mu\text{g/L}$. Of the 25 PCE concentrations listed in Table F14 (including the “not detected” analyses), only 3 computed WTP concentrations or about 12 percent failed the calibration standard. The computed PCE concentration used to compare the PCE concentration determined for the tank sample collected on February 11, 1985, was the January 1985 concentration (176 $\mu\text{g/L}$). The source of the PCE in the tank at a concentration of 215 $\mu\text{g/L}$ could have only been water-supply well TT-23 or TT-26 or both. Service at wells TT-23 and TT-26 was discontinued during February 1985 on an unknown day. Simulated contributions from these wells to the Tarawa Terrace WTP are zero for the entire month of February 1985. Accordingly, the computed WTP PCE concentration for January 1985, prior to removal of wells TT-23 and TT-26 from service, was used as a reasonable surrogate for February 1985. A similar argument is forwarded regarding the analysis of the tap-water sample dated February 2, 1985. The computed WTP PCE concentration for January 1985 is compared to the observed PCE concentration of 80 $\mu\text{g/L}$.

Table F14. Computed and observed tetrachloroethylene (PCE) concentrations in water samples collected at the Tarawa Terrace water treatment plant and calibration target range, U.S. Marine Corps Base Camp Lejeune, North Carolina.

[$\mu\text{g/L}$, microgram per liter; TTWTP, Tarawa Terrace water treatment plant; ND, not detected]

Date	PCE concentration, in µg/L		Calibration target range, in µg/L
	Computed ¹	Observed	
²TTWTP Building TT-38			
5/27/1982	148	180	25–253
7/28/1982	112	³104	33–329
7/28/1982	112	³76	24–240
7/28/1982	112	³82	26–259
2/5/1985	176	³,⁴80	25–253
2/13/1985	3.6	⁵ND	0–10
2/19/1985	3.6	⁶ND	0–2
2/22/1985	3.6	⁵ND	0–10
3/11/1985	8.7	⁶ND	0–2
3/12/1985	8.7	⁶,⁷6.6	2.1–21
3/12/1985	8.7	⁶,⁸21.3	6.7–67
4/22/1985	8.1	⁵1	0.3–3.2
4/23/1985	8.1	⁵ND	0–10
4/29/1985	8.1	⁵3.7	1.2–11.7
5/15/1985	4.8	⁵ND	0–10
7/1/1985	5.5	⁵ND	0–10
7/8/1985	5.5	⁵ND	0–10
7/23/1985	5.5	⁵ND	0–10
7/31/1985	5.5	⁵ND	0–10
8/19/1985	6.0	⁵ND	0–10
9/11/1985	6.0	⁵ND	0–10
9/17/1985	6.0	⁵ND	0–10
9/24/1985	6.0	⁵ND	0–10
10/29/1985	6.0	⁵ND	0–10
²TTWTP Tank STT-39			
2/11/1985	176	⁵215	0–10

¹Weighted-average computation

²See Plate 1, Chapter A report, for location (Maslia et al. 2007)

³Detection limit is unknown

⁴Analysis of tap water sample for Tarawa Terrace, address unknown

⁵Detection limit = 10 $\mu\text{g/L}$

⁶Detection limit = 2 $\mu\text{g/L}$

⁷Sample collected downstream of TTWTP reservoir after operating well TT-23 for 24 hours

⁸Sample collected upstream of TTWTP reservoir after operating well TT-23 for 22 hours

Simulation of Tetrachloroethylene (PCE) Migration

An example of a flow-weighted average computation of PCE concentration is shown in Table F15 for May 1982. Similar computations were accomplished for simulated pumping and PCE concentrations for all 528 stress periods and are plotted in Figure F27. Computed breakthrough of PCE at the MCL concentration of 5 µg/L occurs at the Tarawa Terrace WTP about October or November 1957 and, except when water-supply well TT-26 was temporarily removed from service, continues above 40 µg/L from about December 1959 until the termination of operations at well TT-26 during February 1985. The precipitous declines in PCE concentration noted in Figure F27 represent periods when well TT-26 was temporarily removed from service during July and August 1980 and January and February 1983. The last decline in PCE concentration corresponds to the final removal of well TT-26 from service. The points indicating "observed" PCE concentrations on Figure F27 correspond to the numerical concentrations listed in Table F14.

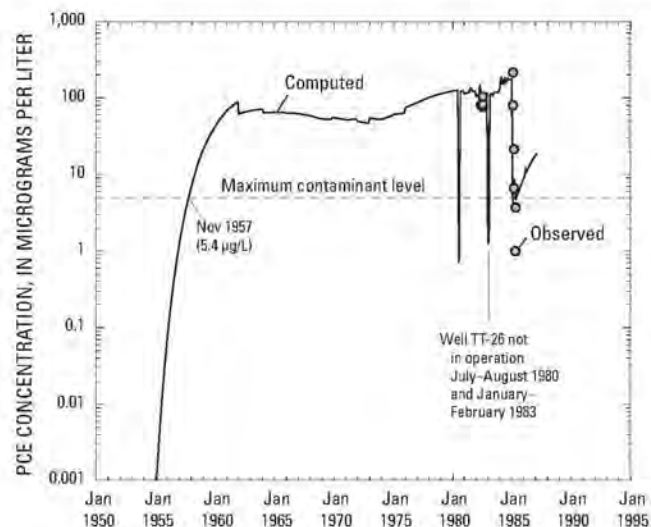


Figure F27. Computed and observed concentrations of tetrachloroethylene (PCE) in finished water at the water treatment plant, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina, January 1951–December 1984. [µg/L, microgram per liter]

Table F15. Example computation of flow-weighted average tetrachloroethylene (PCE) concentration at the Tarawa Terrace water treatment plant, U.S. Marine Corps Base Camp Lejeune, North Carolina, May 1982.

[ft³/d, cubic foot per day; g/ft³, gram per cubic foot; g/d, gram per day; µg/L, microgram per liter]

Site name ¹	Simulated pumping rate, in ft ³ /d	Simulated PCE concentration, in g/ft ³	Simulated PCE flow rate, in g/d	Weighted average PCE concentration, in g/ft ³	Weighted-average PCE concentration, in µg/L
TT-26	25,604	0.02046	523.83		
TT-52	21,000	3.82×10^{-16}	8.027×10^{-12}		
TT-53	14,438	1.93×10^{-8}	0.00028		
TT-54	10,223	6.62×10^{-5}	0.68		
TT-67	10,223	0.00011	1.15		
TT-31	20,021	1.035×10^{-6}	0.021		
TT-25	13,865	4.88×10^{-7}	0.0068		
TT-30	9,626	0.0	0.0		
Total	125,000		525.68	0.00420	148

¹See Figure F1 for location

Sensitivity Analysis

Sensitivity Analysis

Sensitivity analysis of the fate and transport model compared the root mean square error (RMS) related to specified changes in fate and transport model parameters to the RMS of the calibrated model. Calibrated model parameters were changed by factors ranging from 0.5 to 4.0. The parameter change factor of the calibrated model was 1.0 (Figure F28). A total of 29 PCE concentrations were used to compute the RMS and are the numerical concentrations listed in Tables F13 and F14. Analytical results listed as “not detected” were disregarded. Results of the sensitivity analyses are summarized in Figure F28. The RMS of the calibrated model was 337 $\mu\text{g/L}$.

Simulation results are shown to be least sensitive to changes to dispersivity and distribution coefficient. The total change in RMS related to changes in dispersivity across the range of change factors applied to the sensitivity analysis equaled about 13 $\mu\text{g/L}$. Simulation results also are relatively insensitive to changes in distribution coefficient until distribution coefficient values exceed about twice the calibrated value. The maximum change in RMS related to changes in distribution coefficient occurred between parameter change factors 2.0 and 4.0 and equaled about 48 $\mu\text{g/L}$. Simulation results with respect to changes in the mass-loading rate were highly sensitive when the mass-loading rate exceeded the calibrated rate. A maximum change in RMS of about 156 $\mu\text{g/L}$ occurred when the mass-loading rate changed by factors ranging from 0.9 to 1.5 of the calibrated value. Simulation results also were highly sensitive to changes in effective porosity and biodegradation rate. The RMS related to changes in effective porosity declined rapidly from 533 to 311 $\mu\text{g/L}$ when change factors ranged from 0.5 to 1.5 of the calibrated value. Similarly, the RMS related to changes in biodegradation rate increased from 312 to 429 $\mu\text{g/L}$ when change factors ranged from 1.5 to 4.0 of the calibrated value. With the exception of the mass-loading rate, the maximum change in RMS for all parameters between change factors 0.9 and 1.5 was 47 $\mu\text{g/L}$ and related to effective porosity. The average RMS for all parameters, including mass loading, between change factors 0.9 and 1.5 equals 343 $\mu\text{g/L}$ and compares favorably to the RMS of 337 $\mu\text{g/L}$ related to the calibrated model.

Discussion

Results and interpretations described in this report are substantially dependent on the accuracy of water-quality data. Substantial differences, if not outright contradictions, characterize many analyses of duplicate samples collected during various investigations of groundwater and supply-well water quality. During ABC One-Hour Cleaners Operable Unit 1, duplicate groundwater samples collected at hydrocone penetration sites were analyzed using a field mobile laboratory and by a CLP laboratory (Roy F. Weston, Inc. 1992). Results of these analyses are listed in Table F7. Duplicate samples are indicated by the sequential repetition of site names. The mobile laboratory result is listed first in the sequence followed

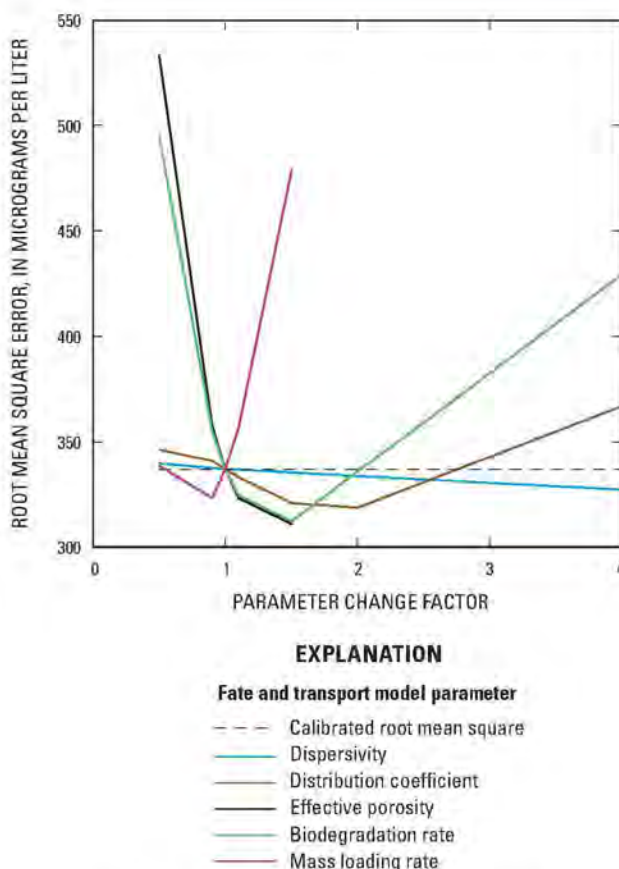


Figure F28. Sensitivity of simulation results to changes in fate and transport model parameters, Tarawa Terrace, U.S. Marine Corps Base Camp Lejeune, North Carolina.

by the CLP laboratory result. Probably the “best” example of analytical “confusion” occurs at site HC-20-34 where the CLP laboratory reported a PCE concentration of 30,000 $\mu\text{g/L}$ and the corresponding mobile laboratory result was 500 $\mu\text{g/L}$. Similar differences obtained to corresponding analyses of TCE at this site. Large differences in PCE concentration determined by the mobile and CLP laboratories also occurred at site HC-21-22, and, to a lesser degree, at several other sites sampled. Such differences in analytical results may have been the result of different or poorly applied analytical techniques but also could be caused by extremely large, in-situ concentration gradients in the subsurface, such that sequential samples of even small quantities of water would contain significantly different quantities of constituent. Substantial vertical concentration gradients are indicated at several sites, including site HC-20, cited previously, and sites HC-21 and HC-44. Reported concentrations of PCE at these locations changed by several orders of magnitude over depth intervals ranging from about 7 to 11 ft.

At water-supply well TT-23, duplicate samples collected on February 19, 1985 (Table F2) were analyzed by JTC Environmental Consultants, Inc., for the U.S. Navy and

by the NCDNRCD Laboratory (Camp Lejeune water document CLW 1482, written communication, April 25, 1986). The reported concentration of PCE in the sample analyzed by JTC Environmental Consultants, Inc., was 26.17 $\mu\text{g/L}$. A PCE concentration in the sample analyzed by the North Carolina laboratory was "not detected."

Analyses of water samples collected at water-supply well TT-26 (Table F2, Figure F16) indicate changes in PCE concentration of several orders of magnitude during relatively short intervals of time. The first available analysis of PCE at well TT-26 was obtained from a sample obtained on January 16, 1985. The well was probably operating in a routine manner at this time and was still supplying water to the Tarawa Terrace WTP. The reported PCE concentration was 1,580 $\mu\text{g/L}$ (Shiver 1985). The PCE concentration reported for a sample obtained on February 12, 1985, at well TT-26 had decreased to an estimated 3.8 $\mu\text{g/L}$, a change of about 2.5 orders of magnitude in only 27 days (Report 29, JTC Environmental Consultants Report 85-052, written communication, February 14, 1985). Seven days later, on February 19, 1985, the reported PCE concentration had increased to about 60 $\mu\text{g/L}$ (Camp Lejeune water document CLW 1482, written communication, April 25, 1986). Although well TT-26 was removed from service some time during February 1985, such radical changes in PCE concentration during this and the previous month are difficult to explain, other than as a result of poor sampling technique or analytical error. The PCE concentrations reported in samples collected at well TT-26 during April, June, and September 1985 ranged from about 600 to 1,200 $\mu\text{g/L}$ and were apparently all determined from analyses at the NCDNRCD Laboratory, as was the sample collected on January 16, 1985. For this study, these analyses are considered the most accurate and representative of PCE concentrations at well TT-26 during 1985.

The accuracy of various analytical methods and technologies used by different laboratories at this time possibly also contributed significantly to conflicting analytical results. Most if not all water-quality analyses cited herein were probably accomplished using GC/MS methodologies. The accuracy of such methods in the 1980s was about ± 20 percent (AH Environmental Consultants, Inc., written communication, June 18, 2004), which possibly explains a number of the conflicting results indicated in Tables F2 and F7.

Sampling methods and techniques probably also affected water-quality results. Little or no information is available regarding sampling methods used at Tarawa Terrace and other Camp Lejeune water-supply wells from 1982 to 1985. In contrast, sampling methods applied at water-supply wells and monitor wells during ABC One-Hour Cleaners Operable Units 1 and 2 are described in detail by Roy F. Weston, Inc. (1992, 1994). These methods included purging water-supply wells from three to five casing volumes before sampling to assure that only aquifer water was sampled. All purge waters were containerized onsite using 500-gal tanks and subjected to regulated disposal. Depending on well construction, 500 gal represented one to about three casing volumes at Tarawa Terrace water-supply wells. Although such methods are generally appropriate, they do not compare to the

routine operation of a water-supply well when pumping occurs continuously for several hours or days. Sampling of discharge water from water-supply wells beyond the accepted sampling protocols may have been necessary to obtain a truly representative sample of aquifer water. For example, water-supply well TT-23 was initially pumped for about 2 hours, beginning March 11, 1985 (Table F2). Capacity of the well at the time was about 250 gal/min. Water samples collected after 2 hours of pumping contained PCE concentrations of about 15 $\mu\text{g/L}$. The well continued pumping for another 22 hours. Water samples collected after this interval contained PCE concentrations of about 41 $\mu\text{g/L}$ (Camp Lejeune water document CLW 1482, written communication, April 25, 1986). Such comparisons indicate that just purging several casing volumes at Tarawa Terrace water-supply wells prior to sampling for PCE and related constituents may not have provided samples representative of the aquifer volume affected during routine operation of the wells and, consequently, possibly contributed to much of the disparity noted between simulated and observed PCE concentrations (Tables F13 and F14).

Comparisons of simulated PCE concentrations at wells to observed concentrations also are not straightforward. Simulated PCE concentrations represent average monthly conditions; whereas, an observed concentration probably represents a condition that occurred during a single day for several minutes or perhaps, at most, an hour. The temporal resolution of flow and MT3DMS simulations was regulated to a substantial degree by project objectives and available data. Monthly resolution was the prescribed protocol for historical reconstruction investigations at U.S. Marine Corps Base Camp Lejeune (ATSDR, Exposure to Volatile Organic Compounds in Drinking Water and Specific Birth Defects and Childhood Cancers, p. 22, written communication, September 2004). Consider, as well, that pumpage quantities used during calibration of the transient flow model (level 2 calibration) were not available for individual water-supply wells at any time and were only available as an annual average of total water supply from 1975 to 1987. Monthly pumpage totals were sporadically available from 1978 to 1987. In addition, monthly water-level data used for transient flow model calibration were generally available at active water-supply wells from 1978 to 1984. Earlier water-level data for water-supply wells were few or none (Faye and Valenzuela 2007). Thus, data limitations and historical reconstruction protocols prescribed a monthly stress period as a rational and appropriate condition for transient flow and MT3DMS model simulations; however, a monthly concentration is not directly comparable to reported PCE concentrations.

The PCE concentrations simulated by the MT3DMS model also were possibly affected by numerical dispersion and the discretization of the time derivative. Substantial numerical dispersion may impart a false accuracy to simulated results. Similarly, an inappropriate discretization of the time derivative frequently causes oscillation of results from time step to time step or from stress period to stress period. Although numerical dispersion cannot be accurately accounted for when using the MT3DMS code, numerical dispersion can be deliberately

Summary

minimized by accommodating a Peclet number ($\Delta x/\alpha_L$) less than 2.0 during the design and calibration of the flow and fate and transport models. The Peclet number was uniformly 2.0 throughout the Tarawa Terrace fate and transport model. Numerical instabilities related to inappropriate time discretization are minimized when the Courant number ($v\Delta t/\Delta x$) is less than 1.0; where v = simulated groundwater-flow velocity, in feet per day; Δt = stress period length, in days; and Δx is as previously defined. The minimum time discretization was a stress period and equaled the number of days in a single month; that is, 28, 29, 30, or 31 days. Stress periods were not subdivided into time steps. Simulated flow velocities ranged between 0.01 and 1.0 ft/d everywhere within the active model domain, except in the immediate vicinity of wells where flow velocities were as great as 8.0 ft/d. Thus, out of a total of about 28,000 active cells per layer, the Courant number was less than 1.0 at all but a few dozen cells near pumping wells. In addition, the sensitivity of simulated concentrations to time discretization was tested by assigning 1-day stress periods to the calibrated fate and transport model from November 1, 1984, to January 31, 1985, and comparing the concentrations simulated by the modified model to those of the calibrated model. Comparisons were made for the days November 30, 1984, December 31, 1984, and January 31, 1985. Pumpage assigned to the months of interest of the calibrated model was assigned to every day of the respective month of the modified model.

Field data and the calibrated model indicated that water-supply wells TT-23 and TT-26 were substantially contaminated with PCE during the test period. Also, concentration gradients simulated by the calibrated model were large in the vicinity of wells TT-23 and TT-26 at this time. Concentrations simulated by the calibrated and modified models were identical prior to stress period 407 (November 1984). The PCE concentrations simulated by the modified and calibrated models during the test period at wells TT-23 and TT-26 are listed in the following table. Simulated concentrations at these wells were similar to the third or fourth significant figure at the designated times whether or not the stress period length was 1 day or 30 days or 31 days. Thus, PCE concentrations simulated by the Tarawa Terrace fate and transport model were demonstrably unaffected by numerical instabilities caused by inappropriate time discretization.

Summary

Migration of PCE from the vicinity of ABC One-Hour Cleaners to Tarawa Terrace water-supply wells TT-23 and TT-26 was simulated using the code MT3DMS integrated with a calibrated groundwater-flow model based on the code MODFLOW96. Simulated mass loading occurred at a constant rate of 1,200 grams per day using monthly stress periods representing the period January 1953 to December 1984. Mass loading occurred at a single cell in the uppermost model layer representing the approximate location of ABC One-Hour Cleaners. Total simulation represented the period January 1951 to December 1994. Until 1984, the vast majority of simulated tetrachloroethylene (PCE) supplied to the Tarawa Terrace water treatment plant (WTP) was contributed by well TT-26. During 1984, well TT-23 was placed in service and also contributed significant quantities of PCE to the Tarawa Terrace WTP. Simulated breakthrough of PCE at well TT-26, the nearest water-supply well to ABC One-Hour Cleaners, occurs during January 1957 at the maximum contaminant level (MCL) concentration of 5 micrograms per liter ($\mu\text{g/L}$). Corresponding breakthrough at well TT-23 occurs during December 1974. Simulated average and maximum PCE concentrations at well TT-26 following breakthrough are 487 $\mu\text{g/L}$ and 851 $\mu\text{g/L}$, respectively. Corresponding concentrations at well TT-23 subsequent to the onset of operations are 219 $\mu\text{g/L}$ and 285 $\mu\text{g/L}$. Concentrations of PCE in finished water at the Tarawa Terrace WTP were computed using a simple mixing model. Flow-weighted PCE concentrations were computed using simulated flow and PCE concentrations at active wells and assigned as the average PCE concentration at the WTP for the appropriate month. Simulated breakthrough of PCE at the Tarawa Terrace WTP occurs at the MCL concentration of 5 $\mu\text{g/L}$ during October or November 1957 and remains at 40 $\mu\text{g/L}$ or more from December 1959 until the termination of pumping at well TT-26 during February 1985. From November 1957 to February 1985, computed maximum and average PCE concentrations at the Tarawa Terrace WTP are 183 $\mu\text{g/L}$ and 74 $\mu\text{g/L}$, respectively.

Site name	Simulated elapsed time, in days	Date	Simulated tetrachloroethylene (PCE) concentration, in gram per cubic foot	
			$\Delta t=1$ day	$\Delta t=30$ or 31 days
TT-23	12,388	Nov. 30, 1984	0.007183956	0.007182317
	12,419	Dec. 31, 1984	0.007214860	0.007211736
	12,450	Jan. 31, 1985	0.007200035	0.007198663
TT-26	12,388	Nov. 30, 1984	0.02297354	0.02298510
	12,419	Dec. 31, 1984	0.02276520	0.02279888
	12,450	Jan. 31, 1985	0.02275406	0.02276190

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Availability of Input Data Files, Models, and Simulation Results

Calibrated model input data files developed for simulating predevelopment groundwater flow, transient groundwater flow, the fate and transport of PCE as a single specie, and the distribution of water and contaminants in a water-distribution system are provided with Chapter A (Morris et al. 2007) of this report in a digital video disc (DVD) format. Public domain model codes used with these input files are available on the Internet at the following Web sites:

- Predevelopment and transient groundwater flow
 - Model code: MODFLOW-96
 - Web site: <http://water.usgs.gov/nrp/gwsoftware/modflow.html>
- Fate and transport of PCE as a single specie
 - Model code: MT3DMS
 - Web site: <http://hydro.geo.ua.edu/>
- Distribution of water and contaminants in a water-distribution system
 - Model code: EPANET 2
 - Web site: <http://www.epa.gov/nrmrl/wswrd/epanet.html>

Specialized model codes and model input data files were developed specifically for the Tarawa Terrace analyses by the MESL at the School of Civil and Environmental Engineering, Georgia Institute of Technology. These specialized codes and input data files were developed for simulating three-dimensional multispecies, multiphase, mass transport (Tech-FlowMP) and pumping schedule optimization (PSOpS) and are described in detail in the Chapter G (Jang and Aral In press 2008) and Chapter H (Wang and Aral In press 2008) reports, respectively. Contact information and questions related to these codes are provided on the Internet at the MESL Web site at: <http://mesl.ce.gatech.edu>.

Readers desiring information about the model input data files or the simulation results contained on the DVDs also may contact the Project Officer of ATSDR's Exposure-Dose Reconstruction Project at the following address:

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Appendix F1. Simulation Stress Periods and Corresponding Month and Year

Appendix F1. Simulation Stress Periods and Corresponding Month and Year**Appendix F1. Simulation stress periods and corresponding month and year.**

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
1	Jan 1951	49	Jan 1955	97	Jan 1959	145	Jan 1963	193	Jan 1967	241	Jan 1971
2	Feb 1951	50	Feb 1955	98	Feb 1959	146	Feb 1963	194	Feb 1967	242	Feb 1971
3	Mar 1951	51	Mar 1955	99	Mar 1959	147	Mar 1963	195	Mar 1967	243	Mar 1971
4	Apr 1951	52	Apr 1955	100	Apr 1959	148	Apr 1963	196	Apr 1967	244	Apr 1971
5	May 1951	53	May 1955	101	May 1959	149	May 1963	197	May 1967	245	May 1971
6	June 1951	54	June 1955	102	June 1959	150	June 1963	198	June 1967	246	June 1971
7	July 1951	55	July 1955	103	July 1959	151	July 1963	199	July 1967	247	July 1971
8	Aug 1951	56	Aug 1955	104	Aug 1959	152	Aug 1963	200	Aug 1967	248	Aug 1971
9	Sept 1951	57	Sept 1955	105	Sept 1959	153	Sept 1963	201	Sept 1967	249	Sept 1971
10	Oct 1951	58	Oct 1955	106	Oct 1959	154	Oct 1963	202	Oct 1967	250	Oct 1971
11	Nov 1951	59	Nov 1955	107	Nov 1959	155	Nov 1963	203	Nov 1967	251	Nov 1971
12	Dec 1951	60	Dec 1955	108	Dec 1959	156	Dec 1963	204	Dec 1967	252	Dec 1971
13	Jan 1952	61	Jan 1956	109	Jan 1960	157	Jan 1964	205	Jan 1968	253	Jan 1972
14	Feb 1952	62	Feb 1956	110	Feb 1960	158	Feb 1964	206	Feb 1968	254	Feb 1972
15	Mar 1952	63	Mar 1956	111	Mar 1960	159	Mar 1964	207	Mar 1968	255	Mar 1972
16	Apr 1952	64	Apr 1956	112	Apr 1960	160	Apr 1964	208	Apr 1968	256	Apr 1972
17	May 1952	65	May 1956	113	May 1960	161	May 1964	209	May 1968	257	May 1972
18	June 1952	66	June 1956	114	June 1960	162	June 1964	210	June 1968	258	June 1972
19	July 1952	67	July 1956	115	July 1960	163	July 1964	211	July 1968	259	July 1972
20	Aug 1952	68	Aug 1956	116	Aug 1960	164	Aug 1964	212	Aug 1968	260	Aug 1972
21	Sept 1952	69	Sept 1956	117	Sept 1960	165	Sept 1964	213	Sept 1968	261	Sept 1972
22	Oct 1952	70	Oct 1956	118	Oct 1960	166	Oct 1964	214	Oct 1968	262	Oct 1972
23	Nov 1952	71	Nov 1956	119	Nov 1960	167	Nov 1964	215	Nov 1968	263	Nov 1972
24	Dec 1952	72	Dec 1956	120	Dec 1960	168	Dec 1964	216	Dec 1968	264	Dec 1972
25	Jan 1953	73	Jan 1957	121	Jan 1961	169	Jan 1965	217	Jan 1969	265	Jan 1973
26	Feb 1953	74	Feb 1957	122	Feb 1961	170	Feb 1965	218	Feb 1969	266	Feb 1973
27	Mar 1953	75	Mar 1957	123	Mar 1961	171	Mar 1965	219	Mar 1969	267	Mar 1973
28	Apr 1953	76	Apr 1957	124	Apr 1961	172	Apr 1965	220	Apr 1969	268	Apr 1973
29	May 1953	77	May 1957	125	May 1961	173	May 1965	221	May 1969	269	May 1973
30	June 1953	78	June 1957	126	June 1961	174	June 1965	222	June 1969	270	June 1973
31	July 1953	79	July 1957	127	July 1961	175	July 1965	223	July 1969	271	July 1973
32	Aug 1953	80	Aug 1957	128	Aug 1961	176	Aug 1965	224	Aug 1969	272	Aug 1973
33	Sept 1953	81	Sept 1957	129	Sept 1961	177	Sept 1965	225	Sept 1969	273	Sept 1973
34	Oct 1953	82	Oct 1957	130	Oct 1961	178	Oct 1965	226	Oct 1969	274	Oct 1973
35	Nov 1953	83	Nov 1957	131	Nov 1961	179	Nov 1965	227	Nov 1969	275	Nov 1973
36	Dec 1953	84	Dec 1957	132	Dec 1961	180	Dec 1965	228	Dec 1969	276	Dec 1973
37	Jan 1954	85	Jan 1958	133	Jan 1962	181	Jan 1966	229	Jan 1970	277	Jan 1974
38	Feb 1954	86	Feb 1958	134	Feb 1962	182	Feb 1966	230	Feb 1970	278	Feb 1974
39	Mar 1954	87	Mar 1958	135	Mar 1962	183	Mar 1966	231	Mar 1970	279	Mar 1974
40	Apr 1954	88	Apr 1958	136	Apr 1962	184	Apr 1966	232	Apr 1970	280	Apr 1974
41	May 1954	89	May 1958	137	May 1962	185	May 1966	233	May 1970	281	May 1974
42	June 1954	90	June 1958	138	June 1962	186	June 1966	234	June 1970	282	June 1974
43	July 1954	91	July 1958	139	July 1962	187	July 1966	235	July 1970	283	July 1974
44	Aug 1954	92	Aug 1958	140	Aug 1962	188	Aug 1966	236	Aug 1970	284	Aug 1974
45	Sept 1954	93	Sept 1958	141	Sept 1962	189	Sept 1966	237	Sept 1970	285	Sept 1974
46	Oct 1954	94	Oct 1958	142	Oct 1962	190	Oct 1966	238	Oct 1970	286	Oct 1974
47	Nov 1954	95	Nov 1958	143	Nov 1962	191	Nov 1966	239	Nov 1970	287	Nov 1974
48	Dec 1954	96	Dec 1958	144	Dec 1962	192	Dec 1966	240	Dec 1970	288	Dec 1974

Appendix F1. Simulation Stress Periods and Corresponding Month and Year

Appendix F1. Simulation stress periods and corresponding month and year.—Continued

[Jan, January; Feb, February; Mar, March; Apr, April; Aug, August; Sept, September; Oct, October; Nov, November; Dec, December]

Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year	Stress period	Month and year
289	Jan 1975	337	Jan 1979	385	Jan 1983	433	Jan 1987	481	Jan 1991
290	Feb 1975	338	Feb 1979	386	Feb 1983	434	Feb 1987	482	Feb 1991
291	Mar 1975	339	Mar 1979	387	Mar 1983	435	Mar 1987	483	Mar 1991
292	Apr 1975	340	Apr 1979	388	Apr 1983	436	Apr 1987	484	Apr 1991
293	May 1975	341	May 1979	389	May 1983	437	May 1987	485	May 1991
294	June 1975	342	June 1979	390	June 1983	438	June 1987	486	June 1991
295	July 1975	343	July 1979	391	July 1983	439	July 1987	487	July 1991
296	Aug 1975	344	Aug 1979	392	Aug 1983	440	Aug 1987	488	Aug 1991
297	Sept 1975	345	Sept 1979	393	Sept 1983	441	Sept 1987	489	Sept 1991
298	Oct 1975	346	Oct 1979	394	Oct 1983	442	Oct 1987	490	Oct 1991
299	Nov 1975	347	Nov 1979	395	Nov 1983	443	Nov 1987	491	Nov 1991
300	Dec 1975	348	Dec 1979	396	Dec 1983	444	Dec 1987	492	Dec 1991
301	Jan 1976	349	Jan 1980	397	Jan 1984	445	Jan 1988	493	Jan 1992
302	Feb 1976	350	Feb 1980	398	Feb 1984	446	Feb 1988	494	Feb 1992
303	Mar 1976	351	Mar 1980	399	Mar 1984	447	Mar 1988	495	Mar 1992
304	Apr 1976	352	Apr 1980	400	Apr 1984	448	Apr 1988	496	Apr 1992
305	May 1976	353	May 1980	401	May 1984	449	May 1988	497	May 1992
306	June 1976	354	June 1980	402	June 1984	450	June 1988	498	June 1992
307	July 1976	355	July 1980	403	July 1984	451	July 1988	499	July 1992
308	Aug 1976	356	Aug 1980	404	Aug 1984	452	Aug 1988	500	Aug 1992
309	Sept 1976	357	Sept 1980	405	Sept 1984	453	Sept 1988	501	Sept 1992
310	Oct 1976	358	Oct 1980	406	Oct 1984	454	Oct 1988	502	Oct 1992
311	Nov 1976	359	Nov 1980	407	Nov 1984	455	Nov 1988	503	Nov 1992
312	Dec 1976	360	Dec 1980	408	Dec 1984	456	Dec 1988	504	Dec 1992
313	Jan 1977	361	Jan 1981	409	Jan 1985	457	Jan 1989	505	Jan 1993
314	Feb 1977	362	Feb 1981	410	Feb 1985	458	Feb 1989	506	Feb 1993
315	Mar 1977	363	Mar 1981	411	Mar 1985	459	Mar 1989	507	Mar 1993
316	Apr 1977	364	Apr 1981	412	Apr 1985	460	Apr 1989	508	Apr 1993
317	May 1977	365	May 1981	413	May 1985	461	May 1989	509	May 1993
318	June 1977	366	June 1981	414	June 1985	462	June 1989	510	June 1993
319	July 1977	367	July 1981	415	July 1985	463	July 1989	511	July 1993
320	Aug 1977	368	Aug 1981	416	Aug 1985	464	Aug 1989	512	Aug 1993
321	Sept 1977	369	Sept 1981	417	Sept 1985	465	Sept 1989	513	Sept 1993
322	Oct 1977	370	Oct 1981	418	Oct 1985	466	Oct 1989	514	Oct 1993
323	Nov 1977	371	Nov 1981	419	Nov 1985	467	Nov 1989	515	Nov 1993
324	Dec 1977	372	Dec 1981	420	Dec 1985	468	Dec 1989	516	Dec 1993
325	Jan 1978	373	Jan 1982	421	Jan 1986	469	Jan 1990	517	Jan 1994
326	Feb 1978	374	Feb 1982	422	Feb 1986	470	Feb 1990	518	Feb 1994
327	Mar 1978	375	Mar 1982	423	Mar 1986	471	Mar 1990	519	Mar 1994
328	Apr 1978	376	Apr 1982	424	Apr 1986	472	Apr 1990	520	Apr 1994
329	May 1978	377	May 1982	425	May 1986	473	May 1990	521	May 1994
330	June 1978	378	June 1982	426	June 1986	474	June 1990	522	June 1994
331	July 1978	379	July 1982	427	July 1986	475	July 1990	523	July 1994
332	Aug 1978	380	Aug 1982	428	Aug 1986	476	Aug 1990	524	Aug 1994
333	Sept 1978	381	Sept 1982	429	Sept 1986	477	Sept 1990	525	Sept 1994
334	Oct 1978	382	Oct 1982	430	Oct 1986	478	Oct 1990	526	Oct 1994
335	Nov 1978	383	Nov 1982	431	Nov 1986	479	Nov 1990	527	Nov 1994
336	Dec 1978	384	Dec 1982	432	Dec 1986	480	Dec 1990	528	Dec 1994



Analyses of Groundwater Flow, Contaminant Fate and Transport, and Distribution of Drinking Water at Tarawa Terrace and Vicinity,
U.S. Marine Corps Base Camp Lejeune, North Carolina: Historical Reconstruction and Present-Day Conditions—
Chapter F: Simulation of the Fate and Transport of Tetrachloroethylene (PCE)